

*Final for  
first year*

INVESTIGATION OF OPTICAL/INFRARED  
SENSOR TECHNIQUES FOR APPLICATION  
SATELLITES

By Irving Kaufman, Principal Investigator

July 1970

Distribution of this report is provided in the interest of information exchange and should not be construed as endorsement by NASA of the material presented. Responsibility for the contents resides in the organization that prepared it.

Prepared under Contract No. NAS 12-2173 by  
Solid State Research Laboratory  
College of Engineering Sciences  
Arizona State University  
Tempe, Arizona 85281

for

Electronics Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FACILITY FORM 602

N70-42367	(ACCESSION NUMBER)	(THRU)
54	(PAGES)	(CODE)
CR-110775	(NASA CR OR TMX OR AD NUMBER)	14
		(CATEGORY)

Reproduced by  
NATIONAL TECHNICAL  
INFORMATION SERVICE  
Springfield, Va. 22151



INVESTIGATION OF OPTICAL/INFRARED  
SENSOR TECHNIQUES FOR APPLICATION  
SATELLITES

By Irving Kaufman

June 1970

Prepared under Contract No. NAS 12-2173 by

Solid State Research Laboratory  
College of Engineering Sciences  
Arizona State University  
Tempe, Arizona 85281

for

Electronics Research Center  
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Mr. Joseph A. Hull  
Technical Monitor  
Code TEO  
Electronics Research Center  
575 Technology Square  
Cambridge, Mass. 02139

Requests for copies of this report should be referred to:

NASA Scientific and Technical Information Facility  
P.O. Box 33, College Park, Maryland 20740

## TABLE OF CONTENTS

	Page
TABLE OF CONTENTS	iii
LIST OF ILLUSTRATIONS	v
SUMMARY	1
INTRODUCTION	2
PRINCIPLES AND VERIFICATION	2
I. PRINCIPLE OF OPERATION	2
II. CONSIDERATION OF SENSITIVITY AND FREQUENCY	7
1. Optical Sensitivity	7
2. Sensitivity of Acoustic System	10
3. Frequency Requirement	11
III. DEMONSTRATION OF PRINCIPLE OF OPERATION	12
SENSOR ARRAY DEVELOPMENT	14
I. ARRAY CONSTRUCTION AND SCANNING	14
1. Series and Parallel Operation of Elements	14
2. Reciprocity	17
3. Metallic Stripe Transducers without Connections	17
4. Two-dimensional Arrays	19
a) Acoustic Waveguides	19
b) Off-Substrate Arrays	19
II. TECHNIQUES	21
1. Metal Deposition	21
2. Photomasking/Selective Etching	23
3. Soldering/Wire Bonding	23
4. Ohmic Contacting	24
5. Miscellaneous	24
III. OPERATION OF SENSING ARRAYS	24
1. Slabs of Single Crystal CdS	24
2. CdS Bars	25
3. Discrete Photoconductors	28
4. Photodiodes	28
IV. ACOUSTICS	33
1. Transducer Fabrication and Operation	33
2. Acoustic Waveguiding	33

V. PHOTOCONDUCTIVE MATERIAL	35
VI. CIRCUITS	36
Requirement on Photoconductivity of Off-Substrate Array	36
Choice of Parameters and Configuration	37
Auxiliary Circuits	42
a) Tone Pulser	42
b) Video Detection	42
SUMMARY AND PLANS	44
REFERENCES	46
PERSONNEL	47
PUBLICATIONS AND CONFERENCE PRESENTATIONS	48

## List of Illustrations

<u>Figure</u>		<u>Page</u>
1	Self-scanning Sensor Array	4
2	Elemental Circuit of Scanning Sensor Array	5
3	Wave Shapes for Self-Scanning Sensor Array	6
4	Approximation used in Calculation of Sensitivity to Light	8
5	Verification of Principle of Operation of Self-Scanning Sensor Array	13
6	Physical Separation of Photoconductive Material from Acoustic Wave Transducers	15
7	Operation with Photoconductive Cell in Series with Acoustic Transducer	16
8	Scheme of Using Transducers in Series	18
9	Two-dimensional Sensor Array-Acoustic Waveguides	18
10	Two-dimensional "Off-Substrate" Sensor Array	20
11	Two-dimensional "Off-Substrate" Array	22
12	Operation of Array of Acoustic Transducers Shunted by Photoconducting CdS Bars	26
13	Output Signal for Half-Sine Wave Pulse Input to CdS Bar Array	27
14	Sensor Array - Discrete Photoconductors	29
15	Output Signals	30
16	Photograph of Sensor Array	31
17	Sensor Array - Photodiodes	32
18	Input and Output Signals	32
19	Photograph of 10 MHz Transducers - 0.4 mm Beam Width	34

Figure

20	Response of narrow-width Transducers	34
21	$V_T/V_{INPUT}$ for series and Shunt Modes	38
22	$V_T/T_{INPUT}$ for series Mode Operation	40
23	$V_T/V_{INPUT}$ for Shunt Mode Operation	41
24	Tone Pulser	43
25	Detection Circuit	45

INVESTIGATION OF OPTICAL/INFRARED  
SENSOR TECHNIQUES FOR APPLICATION  
SATELLITES

By Irving Kaufman

Solid State Research Laboratory  
College of Engineering Sciences  
Arizona State University  
Tempe, Arizona 85281

SUMMARY

This is the Final Report of the first year of effort of a study of optical sensor arrays constructed of piezoelectric and photoconducting materials and excited by short voltage pulses of predetermined shape, to generate output electrical signals that are time analogs of a spatial distribution of light.

In the construction of solid state arrays for optical sensing the problem of scanning the sensor elements is of great importance. The work of this contract, reported herein, deals with a method of self-scanning of such arrays that employs short acoustic pulses that travel on a piezoelectric medium. In the design originally proposed, this medium is coated with a photoconducting layer. The various degrees of intensity of illumination of an image focused on this layer cause the various portions of the layer to be photoconducting by different amounts, thereby "shorting out" the electric fields of acoustic pulses traveling on the piezoelectric medium by corresponding amounts. The result is a time analog of the spatial distribution of light of the image.

Described in this report are:

1. The self-scanning scheme.
2. Initial demonstration of the principle of operation.
3. Progress in our techniques of generating and controlling acoustic surface waves, including laboratory techniques developed during the course of this contract.
4. Our initial efforts of depositing photoconducting material.
5. Demonstration of a multi-element one-dimensional array sensor.
6. Design considerations.
7. Schemes for separating the sensing elements from the piezo-electric line; two-dimensional arrays.



## INTRODUCTION

Because of the well-known advantages of solid state devices over vacuum tubes, there is currently a great interest in the development of image sensors that produce a video signal without the help of an electron beam. Such an image sensor consists, in principle, of an array of photo-sensitive elements that are connected to scan generators and video coupling circuits, whose functions are to generate an electrical signal that is the time analog of the spatial distribution of the light intensity of the image. To produce image details comparable to, say, commercial television, the array must contain many thousands of elements. The scanning of such an array is a formidable problem.

Some success toward the solution of this problem has been achieved by the use of integrated semiconductor circuitry and a charge storage technique, with video signal output very similar to the method used in a Vidicon (Ref. 1).

The technique proposed by us differs from the all-semiconductor array in that horizontal scanning is accomplished by acoustic pulses that propagate in a piezoelectric substrate or material with a piezoelectric overlay, and that the video signal is derived in a different manner.

It is still too early to form a real comparison between this acoustic system and others, for our work this first year has been strictly exploratory. In addition to the quality of performance of the various systems, after they have been developed, deciding factors for their use will also be their cost and reliability.

## PRINCIPLES AND VERIFICATION

### PRINCIPLE OF OPERATION

The application of elastic wave techniques to the self-scanning image sensor was suggested by the propagation velocity and by the spatial resolution achievable with such waves. For example, let us consider a 500 dot-line on alpha-quartz that is to be scanned by a 50 MHz acoustic wave. In this line, let each dot be the width of a 50 MHz acoustic wavelength (0.0064-cm). Then the line length is 3.2 cm and the scanning time is 10 microseconds. While this scan time per line is not the same as that of standard commercial television, it is comparable to the scan times used therein. As for resolution, there is good reason to believe that the resolution for an acoustic pulse could be of the order of an acoustic wavelength - which here is 0.0064 cm and therefore a very small distance.

In the one-dimensional image sensor configuration described originally, we considered the use of an acoustic delay line made of a material

that was both piezoelectric (for excitation of acoustic pulses) and photoconducting (for optical sensing). The objective was to use light for controlling the local "piezoelectric activity," since the light-generated local conductivity of this material would "short out" local piezoelectric fields.

If acoustic waves propagating in the bulk of the material are used for such a sensor, then the material must indeed be both piezoelectric and photoconducting. If the acoustic waves can be confined to the surface of the material only, however, then the same effect can be achieved simply by placing a photoconductor adjacent to a piezoelectric surface. A schematic of a prototype configuration for this simpler scheme is shown in Figure 1.

Here an array of acoustic surface wave transducers is evaporated on a piezoelectric substrate. Connected in series between each transducer and a common source is a resistor. Deposited on top of the array is a layer of photoconducting material. The spatial period between identical transducer elements is chosen to be the acoustic wavelength  $\lambda$  of the RF signal exciting the array.

To clarify the operation of this sensing array, we examine two adjacent transducer elements, as in Figure 2(a). When these elements are in the dark, the photoconducting material exerts negligible resistive shunting; so that the equivalent circuit is as in Figure 2(b). If  $R$  is chosen to be considerably smaller than the reactance of the transducers, nearly the full source voltage will then exist across the transducer elements. Under illumination, however, the photoconductive material causes the equivalent circuit to be that of Figure 2(c). With sufficient photoconductivity, so that  $R' \ll R$ , only a small fraction of the source voltage appears across the transducers. Accordingly the voltage across the transducers, and therefore the amount of elastic signal generated, is a function of the light intensity.

Returning to the array, we consider (a) the array in the dark; (b) the array illuminated with spatially varying light intensity.

We now excite the array with the half sine wave pulse of Figure 3(a). For the "dark" condition, nearly the full voltage exists across each of the transducer elements. All transducers therefore develop an elastic signal of approximately the input pulse shape and of equal amplitude. Because of the reversal of polarities in adjacent transducers and of the spatial distribution of the transducer elements, the voltage developed across the output transducer by the elastic signal arriving from the left has the shape of Figure 3(b).

Next we consider the case of a spatial distribution of light on the transducer elements, as in Figure 3(c). Because of the photoconducting material, those transducer elements that receive a strong light are now shunted by low resistance, the elements in the dark are shunted only

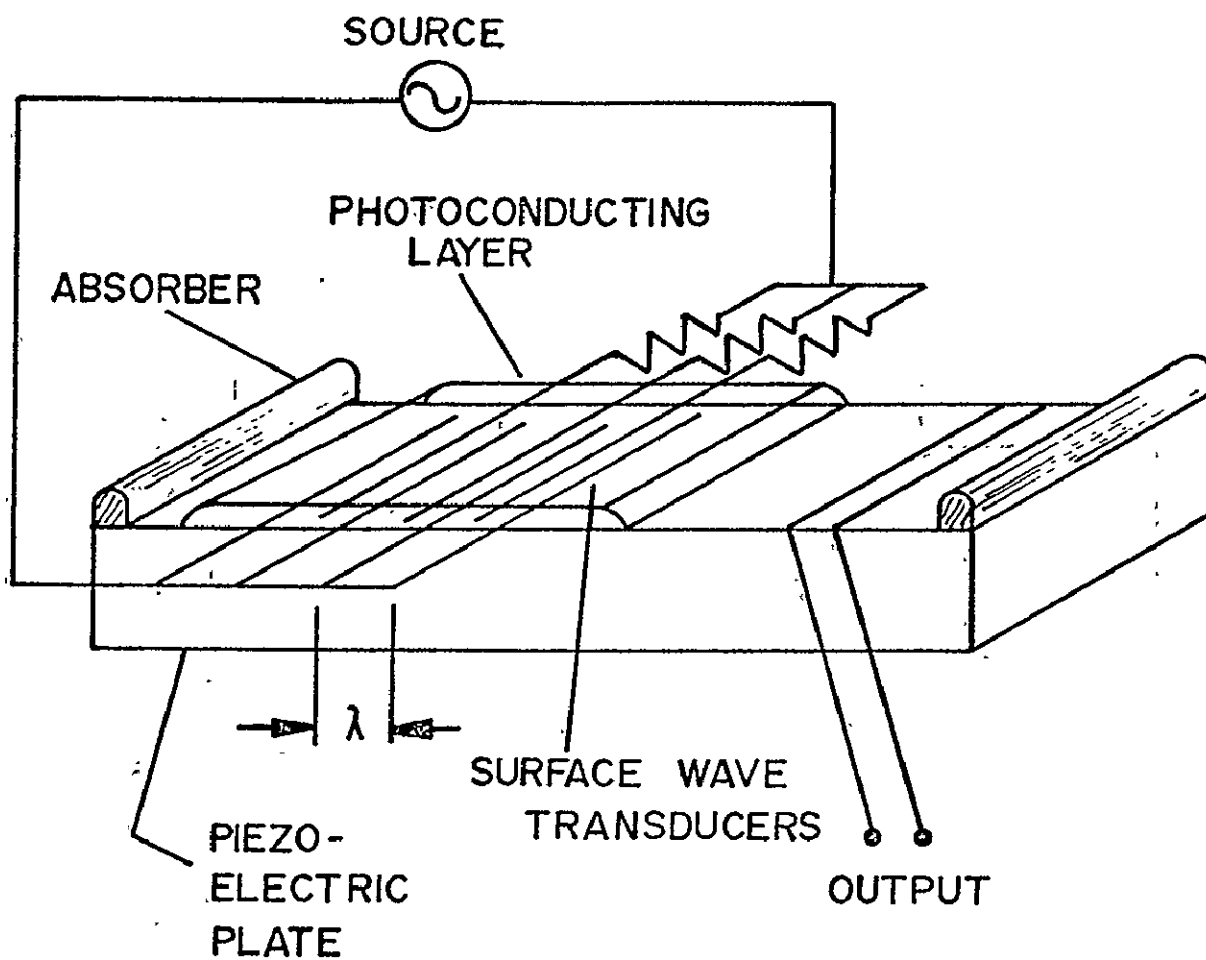


Figure 1. Self-scanning sensor array constructed of acoustic surface wave transducer elements overlayed by photoconducting material.

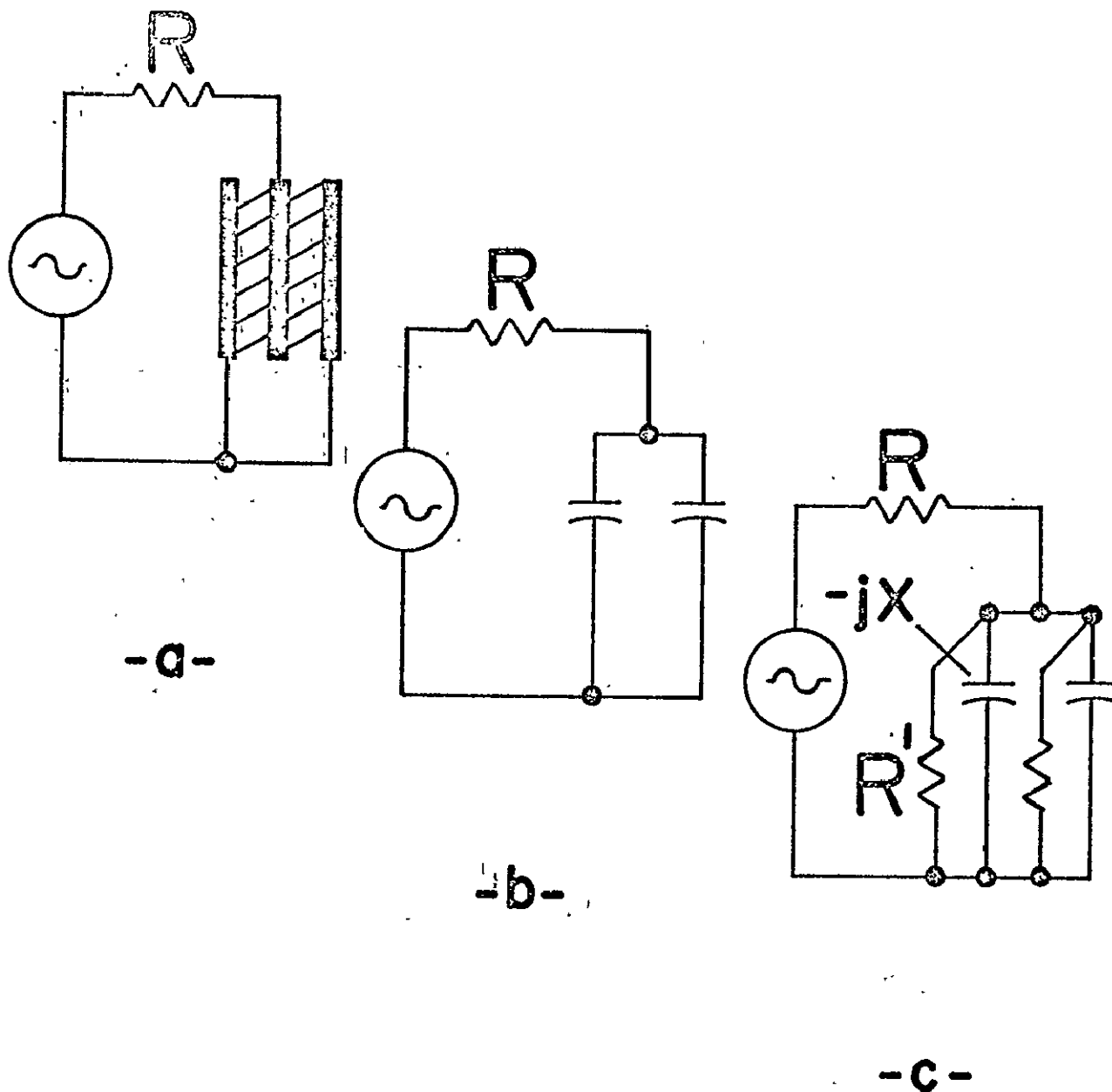


Figure 2. Elemental circuit of scanning sensor array.

- (a) Elemental circuit of source, resistor, and acoustic transducer shunted by photoconducting material.
- (b) Equivalent circuit in the dark.
- (c) Equivalent circuit under illumination.

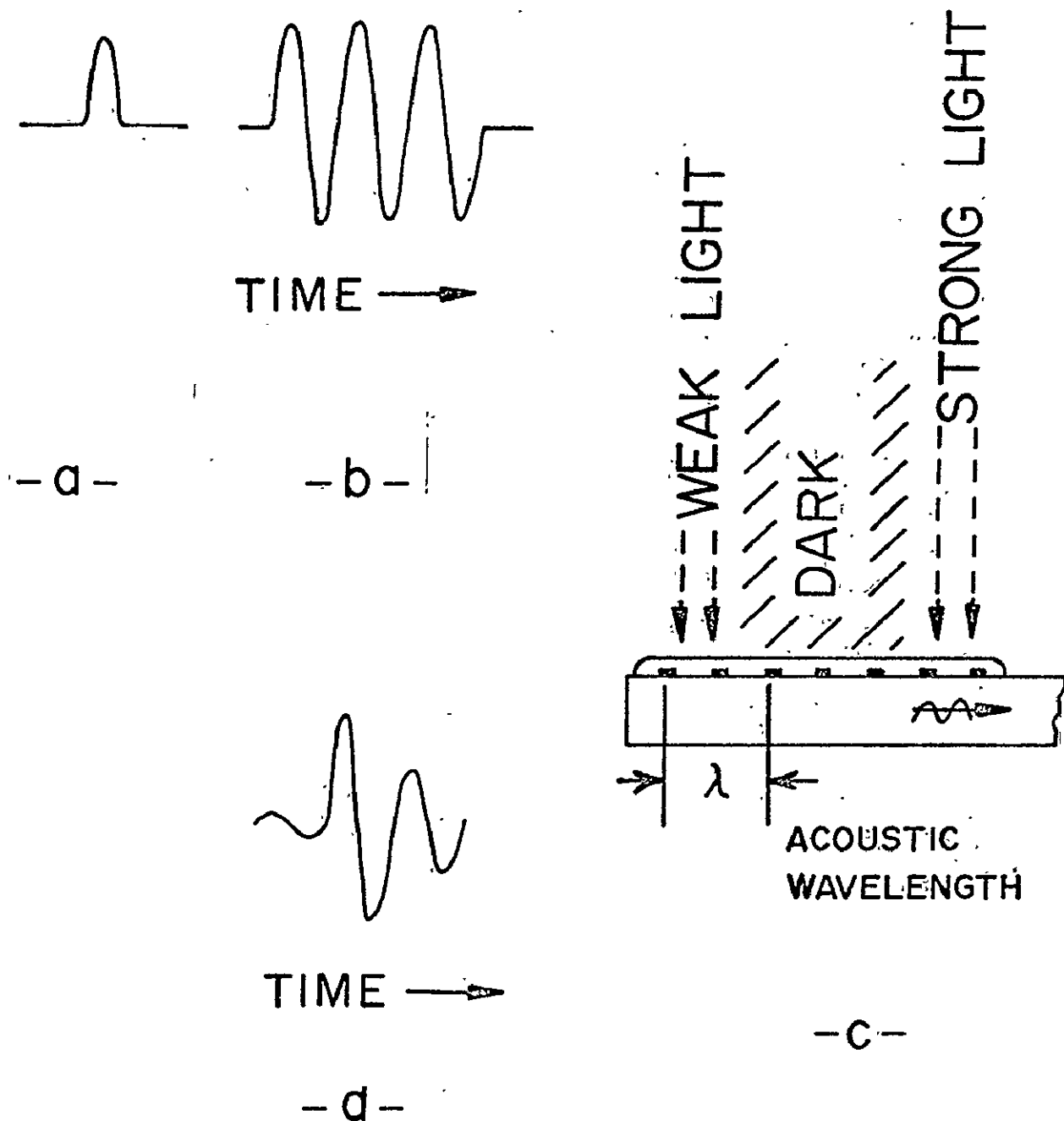


Figure 3. Wave shapes for self-scanning sensor array.

- (a) Input voltage pulse.
- (b) Acoustic signal generated by array when in the dark.
- (d) Acoustic signal generated by array for the illumination pattern of (c).

negligibly, as before. Consequently, the voltage that appears across the various transducers and the elastic signal generated by them during the "on" time of the pulse varies inversely with the intensity of illumination. The output voltage is thus as in Figure 3(d). Demodulation of this signal yields a time analog of the spatial distribution of light on the surface of Figure 3(c). A spatial distribution of light has, accordingly, been sensed and converted into an electrical signal.

## II. CONSIDERATION OF SENSITIVITY AND FREQUENCY

### Optical Sensitivity

To see if the sensitivities achievable with such a scheme would be sufficient for the sensing of an image in, say, ordinary light levels, we based our expectations on the following estimate.

A simple equivalent circuit of acoustic transducers used as described in Section I, is given in Figure 2. Here the capacities shown are the capacities of the transducer stripes,  $R'$  is the resistance that shunts the stripes because of the photoconductivity of the light-sensing material. If this circuit is to be responsive to light, then  $R'$  under full illumination should be of the order of magnitude of the reactance of the capacitor that shunts it, or lower. Accordingly, we look at the possibilities of this case by examining the resistance possible.

We start our estimate with the aid of Figure 4, where two transducer stripes are approximated by two parallel wires.\* The capacity per unit length of this system is  $C_0 = [27.8 \epsilon' / \ln(b/a)] [10^{-12}]$  f/m, where  $\epsilon'$  is the relative dielectric constant of the medium in which these wires are imbedded. Letting  $\epsilon' = 4$  and  $b/a = 4$ , we find  $C_0 = (8)(10^{-11})$  f/m. At 50 MHz, therefore,  $X$  is  $40/L$  ohms where  $L$  is the length (in meters) that the transducer extends perpendicular to the paper.

Now, for 50 MHz, the center to center spacing of conductors is  $\lambda/2 = (3.2)(10^{-5})$  meters.

If the resistance  $R'$  (under illumination) just equals  $X$ , then we require  $R' = 40/L$ . If the thickness of photoconducting material is 1 micron, then its resistivity is

$$\rho = (40/L)(10^{-6})(L)/(1.6)(10^{-5}) \text{ ohm-meters} = 2.5 \text{ ohm-meters.}$$

The conductivity required is there  $\sigma = \rho^{-1} = 0.4 \text{ (ohm-meters)}^{-1}$ .

Corresponding to a carrier mobility of  $0.1 \text{ m}^2/\text{volt-sec}$  ( $1000 \text{ cm}^2/\text{volt-sec}$ ), this represents a light-generated carrier density of

\*Much more exact calculations of capacity and resistance have been made since this early estimate. Calculations on the sensitivity of various circuit configurations are in progress at the present time.

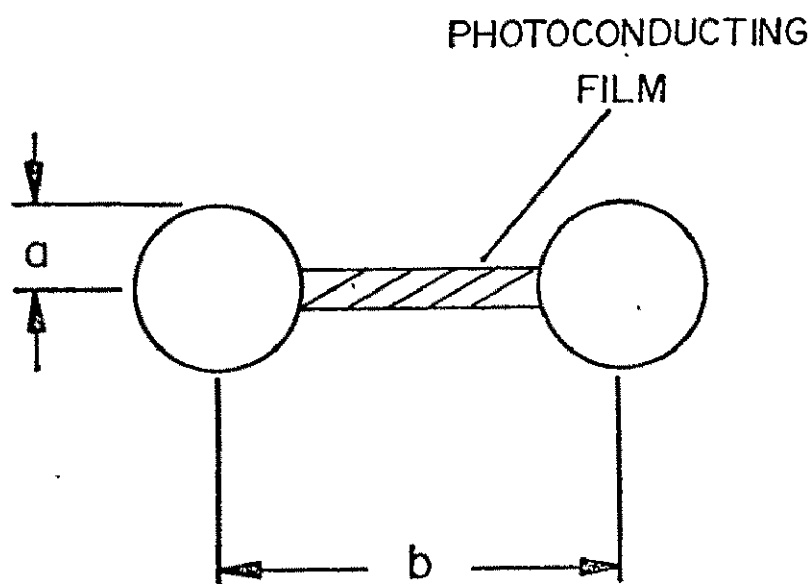


Figure 4. Approximation used in calculation of sensitivity to light.  
The circles are conducting wires.

$$n = \sigma/\mu q = (0.4)/(0.1)(1.6)(10^{-19}) \\ = (2.5) 10^{19} \text{ electrons/m}^3$$

The carrier density per unit area is therefore

$$n_s = (n)(10^{-6}) = (2.5) 10^{13} \text{ electrons/m}^2.$$

To create these carriers with light, assuming a quantum efficiency of 10%, requires an energy of  $n_s hf/0.1$ , where  $h$  is Planck's constant;  $f$  is the optical frequency.

Here we find, for 6000 Å light,

$$n_s hf/0.1 = (2.5)(10^{13})(6.63)(10^{-34})(5)(10^{14})/0.1 \\ = (8.3)(10^{-5}) \text{ joules/m}^2.$$

For a carrier effective lifetime of  $10^{-2}$  seconds, commensurate with TV sweep rates, the optical power density required is therefore

$$(8.3)(10^{-5})/10^{-2} = (8.3)(10^{-3}) \text{ watts/m}^2 \\ = (8.3)(10^{-7}) \text{ watts/cm}^2.$$

To see how this compares to the light levels of daylight, we refer to the data of Fink (Ref. 2). Here, for images focused through a lens of f-number  $F$ , the power density at the image, for negligible lens losses, is given by

$$E' = \frac{\pi B}{4F^2}, \text{ where}$$

$E'$  = illuminance (in foot-candles) at image plane;

$B$  = luminance of the extended surface that is to be focused (in candles per sq. ft.);

$F$  = the f-number of the lens.

After some unit conversions, this becomes

$$E' \simeq ((4) 10^{-7} B)/F^2, \text{ with}$$

$E'$  = power density at image plane, in watts per sq. cm;

$B$  = luminance of surface, in foot-lamberts.

(This equation actually gives a smaller number of watts/cm<sup>2</sup> than would exist for white light, for we have used the conversion factor of 1 watt =



680 lumens, which is true only for 5550 Å light.)

Typical values of B are given in Table I (Ref. 3):

TABLE I  
TYPICAL LUMINANCE VALUES

<u>Subject</u>	<u>Luminance (Foot Lamberts)</u>
Sun at Zenith	(4.82)(10 <sup>8</sup> )
Perfectly reflecting, diffusing surface in sunlight	(9.29)(10 <sup>3</sup> )
Moon, clear sky	(2.23)(10 <sup>3</sup> )
Overcast sky	(9-20)(10 <sup>2</sup> )

Using the relation for E', above, we therefore find the power densities at the image plane for an f/2 lens given in Table II.

TABLE II  
SURFACE POWER DENSITIES

<u>Subject</u>	<u>Watts/cm<sup>2</sup></u>
Sun at Zenith	48
Perfectly reflecting, diffusing surface in sunlight	(9)(10 <sup>-4</sup> )
Moon, clear sky	(2)(10 <sup>-4</sup> )
Overcast sky	≈ 10 <sup>-4</sup>

Since the power density required for our prototype self-scanning optical sensor array was found to be of the order of 10<sup>-6</sup> watts/cm<sup>2</sup>, we can conclude from Table II that such a sensor array should have sufficient sensitivity for Vidicon-type of operation.

## 2. Sensitivity of Acoustic System

Before this work on the self-scanning sensing array was initiated, no experiments dealing with conversion of half-cycle signals to surface waves and reconversion to electrical signals by single pair surface wave transducers had been reported. However, extrapolating from the work reported by Arzt *et al* (Ref. 4), we estimated that such single pair surface wave transducers on quartz of 7 mm width should provide sufficient coupling to the quartz to allow a signal-to-noise ratio of at least 36 db in the signal coupled out. Subsequent experimental work has substantiated that the coupling in and out of pulses with single-pair transducers does not present a problem - at least with transducers of several millimeters width. We are presently investigating how far this technique can be pushed when the acoustic line is reduced to widths that are of the order of half of an acoustic wavelength. (See p. 33.)

### 3. Frequency Requirement

The minimum width of the pulse that can be applied to the line as a scan pulse is determined by the scan rate desired. Since this pulse is nominally a half-cycle of a sine wave, its length determines the frequency of operation, for the width of the transducer pair is to be  $\lambda/2$ , where  $\lambda$  is the acoustic wavelength that corresponds to the frequency of that sine wave. We now let

$F$  = frame rate of scanning an array composed of  $N$  narrow acoustic waveguides, in which each functions according to the method of Section I ;

$E$  = the number of resolved elements per acoustic waveguide.

Then the time allotted per line is  $1/FN$ . Consequently, if each element of the line is to be "heard from," the transit time of an acoustic pulse across the line must be somewhat less than  $1/FN$ .

Although the line in our system is composed of an array of half-wave ( $\lambda/2$ ) transducers, the resolution is actually  $\lambda$ , as seen by the waveshapes of Figure 3. The transit time of an acoustic pulse across a simple line is therefore  $\lambda E/v$ , where  $v$  is the velocity of acoustic waves of the surface wave mode used.

We therefore require that

$$\lambda E/v < 1/FN$$

Since  $v/\lambda$  is the frequency  $f$  of the acoustic wave, we therefore require  $f > EFN$ .

If we take specific values of  $E = 250$  elements per line,  $F = 30$  frames per second, and  $N = 250$  lines, we find that we must have  $f > 1.875$  MHz. Acoustic signals of this frequency range are very easy to produce.

In practice, it will be desirable to use frequencies higher than 1.875 MHz, for a line that contains 250 wavelengths of a 1.875 MHz wave would be 0.426 meters wide. Frequencies in the range from 10 MHz to 50 MHz, which are also easy to generate, are therefore more appropriate, for these higher frequencies (shorter pulses) reduce the line widths to practical dimensions. While they also now cause a "dead time" between pulsing of adjacent lines to exist, so that the scanning system is no longer directly compatible with commercial television, this should be no problem for various applications. Moreover, it is quite likely that means for conversion of the video output into a compatible signal can be devised.

### III. DEMONSTRATION OF PRINCIPLE OF OPERATION

The first demonstration of the principle of the self scanning array sensor was made with a prototype array of six 1 MHz surface wave transducers that were deposited on alpha quartz and overlayed with a slab of Cadmium Sulfide (CdS) of very high "dark" resistivity and resistivity in room light of  $10^4$  ohm-cm. Because of ohmic contacting difficulties, in this initial experiment metallic contact was made to only one of the transducers, as shown in Figure 5(a); so that only the signal from the transducers would be appreciably affected by the light. Figures 5(c) and 5(d) show the output voltages that were obtained with the 1 microsecond input voltage pulse of Figure 5(b). Of relevance in these two figures are the pulses of the central wave trains, indicated in the figure by letters A through F. (The others were extraneous pulses that originated because of bulk wave generation or electrostatic pickup.) Separate tests, using the simple technique of "shorting" the transducers individually, showed the lettered pulses to originate from the various transducers lettered correspondingly in Figure 5(a).

Of significance is that:

(1) Pulses could be identified as originating from individual transducers. This means that the bandwidth of one of these transducers is sufficiently wide so as to permit fairly accurate reproduction of a half-cycle-sine-wave pulse.

(2) The principle of self-scanning/sensing is verified. This is seen by comparison of Figures 5(c) and 5(d). Figure 5(c) is the signal derived from an output acoustic transducer located to the right of the input transducer array while the entire system was in darkness. 5(d) is the same output signal, but with room lights turned on. As expected, the amplitudes of pulses B and C, which originated from the transducers that were shunted by CdS, were highly attenuated because of the presence of the light.\*

This test therefore demonstrated the operation of a prototype self-scanning array sensor.

\*It may be noted that even in the dark, the pulses from transducers B and C were somewhat lower in intensity than those from A, B, E, F, and G. This was because the presence of the CdS increased the capacitance of transducers B and C. Had the other transducers been "loaded" with CdS also, their "dark" voltage would have decreased in the same manner.

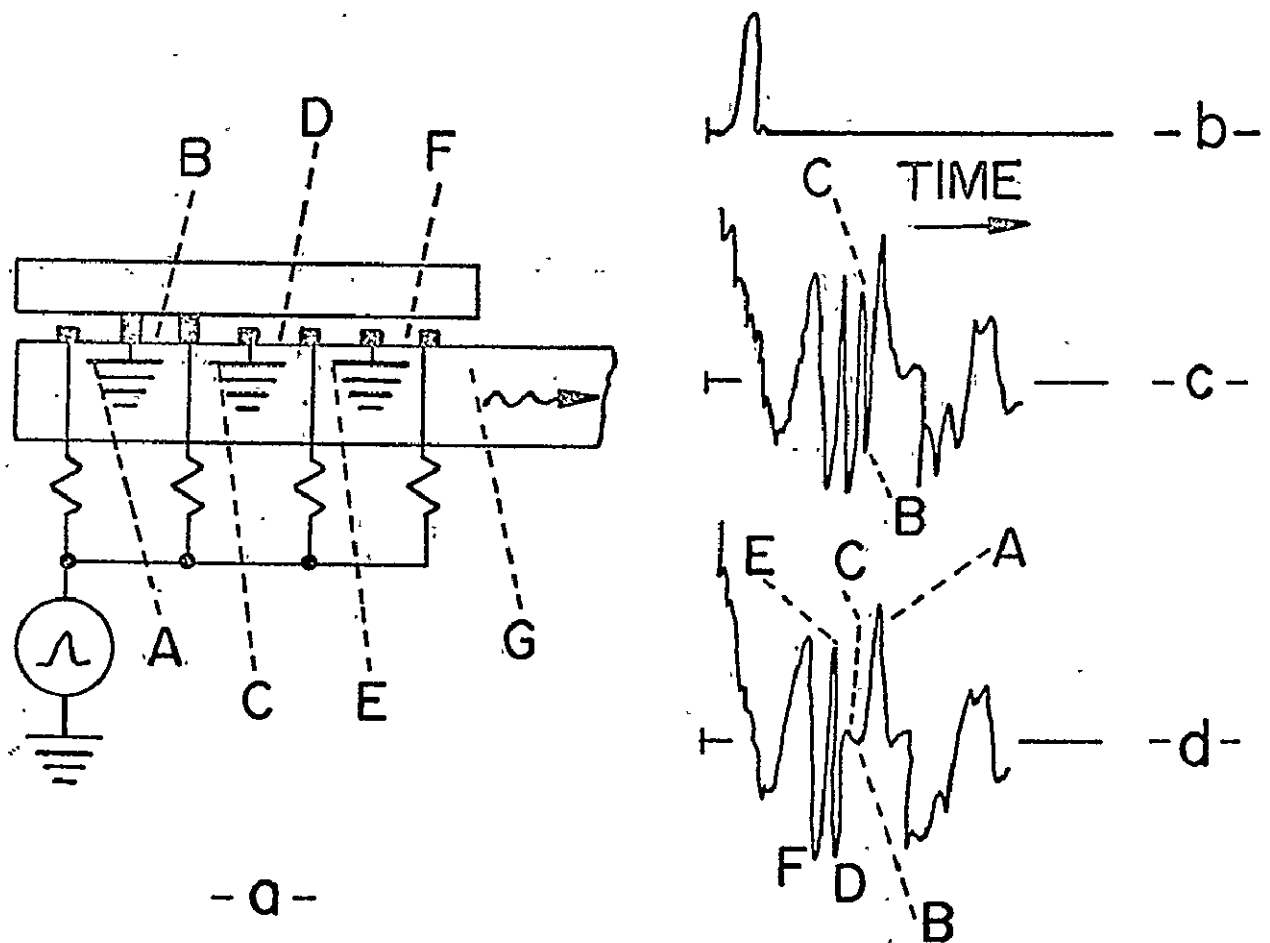


Figure 5. Verification of principle of operation of self-scanning sensor array.

(a) Experimental arrangement. Here a slab of photoconducting CdS is connected across transducer B.

(b) Input pulse.

(c) Replica of output signal from a transducer pair far to the right of G when array was in the dark.

(d) Same as (c), but array illuminated by room lights.

## SENSOR ARRAY DEVELOPMENT

The development of the principle of operation of the acoustically self-scanned optical array sensor into a two-dimensional working model has a number of facets. In this section we discuss our ideas and activities of these various aspects of this problem.

### I. ARRAY CONSTRUCTION AND SCANNING

#### 1. Series and Parallel Operation of Elements

In the scheme of the optical array sensor proposed and discussed in the early part of this report, a series of piezoelectric surface wave transducers are excited in parallel (through individual resistors). Each transducer pair is coated with photoconducting material, in the manner of Figure 1. Varying degrees of illumination falling on the different transducers-photoconductors act to shunt the transducers by amounts depending on the degree of illumination.

While this scheme may yet be the one to be used in an actual array sensor, we have been considering modifications that may offer advantages.

The most obvious extension is the separation of the photoconducting cell from the acoustic substrate, as shown in Figure 6. This separation is of great importance in the formation of two-dimensional arrays, as discussed in Section I-4, below.

An additional advance made was the suggestion and operation of a sensor cell in a series mode of operation, shown in Figure 7. In this mode, the photoconducting cell is in series with the piezoelectric transducer. The transducer voltage  $V_{AB}$ , which determines the signal conversion to the acoustic system, could vary here from a minimum of zero to a maximum of impressed voltage  $V_{AC}$ , depending on whether the photoconducting material is in the dark or strongly illuminated. The output signal for an array of such piezoelectric-photoconducting elements is therefore a time-varying signal composed of a series of pulses whose instantaneous intensities are the analog of the illumination pattern falling on the various elements of the array.

This series scheme has the advantage of eliminating the necessity for the series resistor (per element) that is required in the shunt system (See Figure 6). Like the shunt system, it also lends itself to the construction of off-substrate arrays.

An equivalent circuit for one element used for this series mode of operation is given in Figure 7(b). Here we note that in addition to the resistance of the photoconducting material we must also include the capacitance of the photoconducting cell and the impedance that accounts for conversion of energy from electrical to mechanical form. This combination of resistive and reactive elements acts to cause the shape of

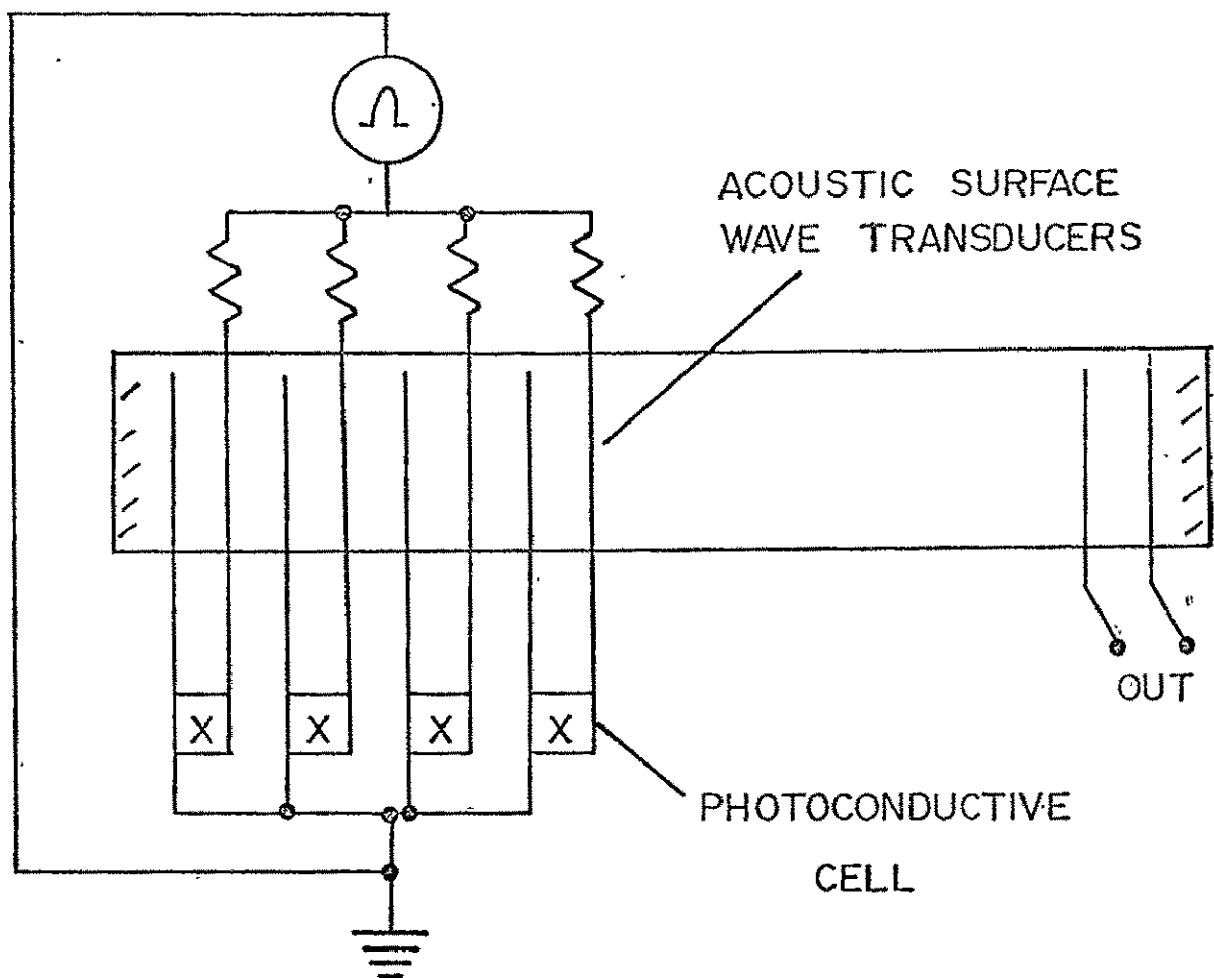
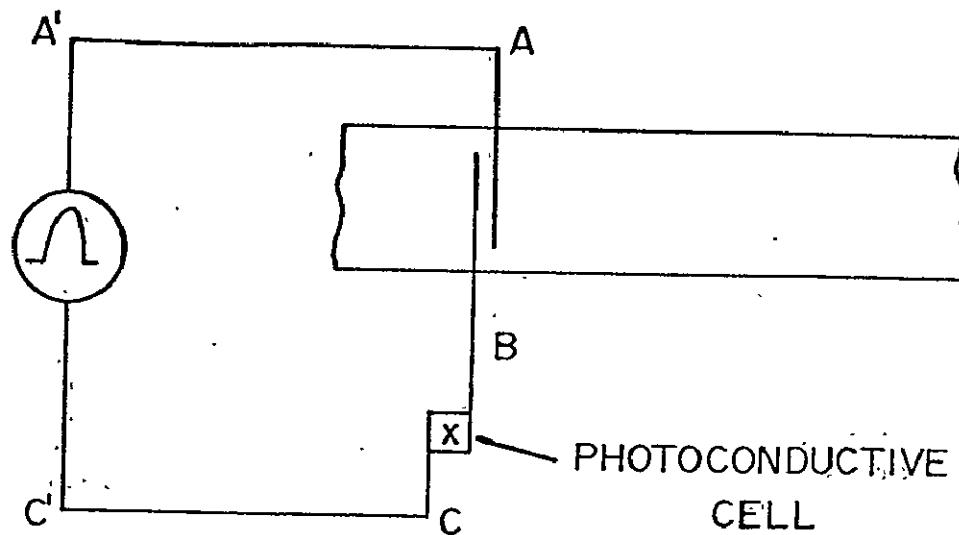
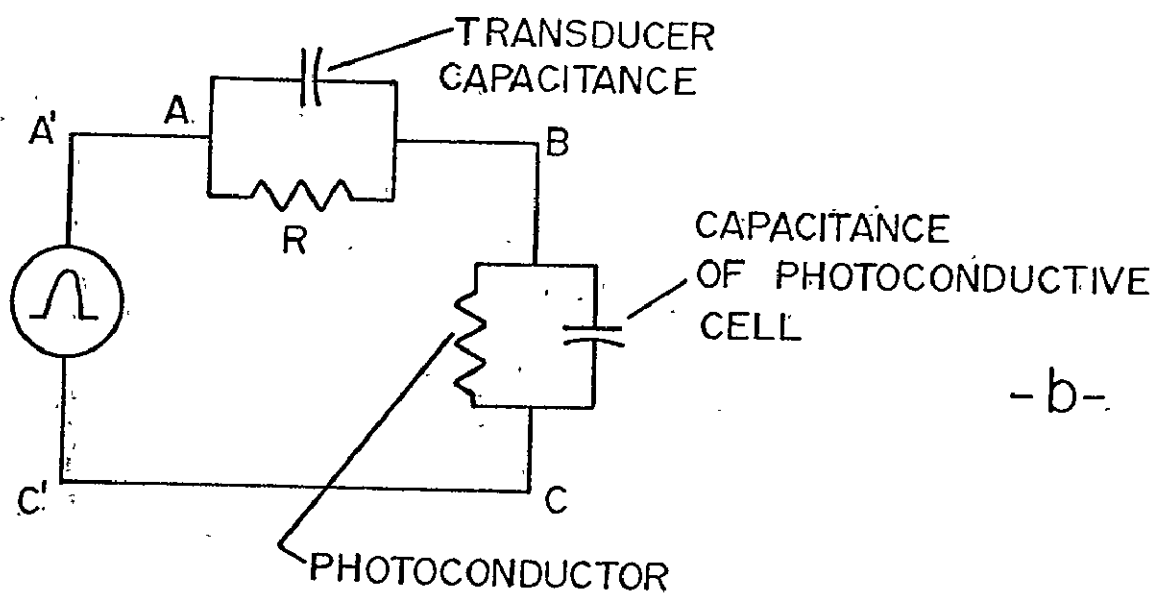


Figure 6. Physical separation of photoconductive material from acoustic wave transducers.



-a-



-b-

Figure 7. Operation with photoconductive cell in series with acoustic transducer.

(a) Schematic.

(b) Equivalent circuit.

output pulses to be different than that of the input pulse. Some circuit modifications may be required for correcting this difficulty.

We are presently engaged in a program of calculations to determine the relative advantages of series and shunt modes of operation. Some discussion of this work is given on pages 37 to 41.

## 2. Reciprocity

In the schemes outlined above, the photoconducting sensing elements are connected to the input transducers. Since the transducers and delay lines are all reciprocal devices, it is also possible to operate the structure in reverse. In such a configuration, a signal pulse, i.e., the scanning signal is applied to a single transducer, while the transducers that are connected to the photoconducting sensing elements are used as output transducers. We have found this scheme operable in the laboratory.

This system has the advantage over that originally proposed that:

- a. Voltage pulses of relatively high amplitude ( $\approx 50$  V.) can be applied to the single-pair transducer without damaging this transducer. The voltage pulses at the output end, where the sensing elements are, will now be sufficiently low so that there need be no fear of damaging these elements, even if they should be photodiodes or phototransistors with a maximum voltage limitation.
- b. In a two-dimensional scheme, in which a shift register is used for switching from line to line (see Section I-4), it is much easier to work with the low voltage pulses of this reversed system than with the higher voltage pulses of the original scheme.

While we have found this reversed system operable in the laboratory, its use in an actual array sensor will await completion of the calculations on array sensitivity.

## 3. Metallic Stripe Transducers Without Connections

A possible simplification suggested in the construction over the method in which each transducer is connected to the generator (or output circuit, using the method of the preceding section), is given in Figure 8. Here a pulse from a constant current generator is sent through the entire array. The voltage developed across each transducer in this system will vary directly with the resistance shunting the element; so that the output waveforms will again contain information of the distribution of the spatial illumination pattern.



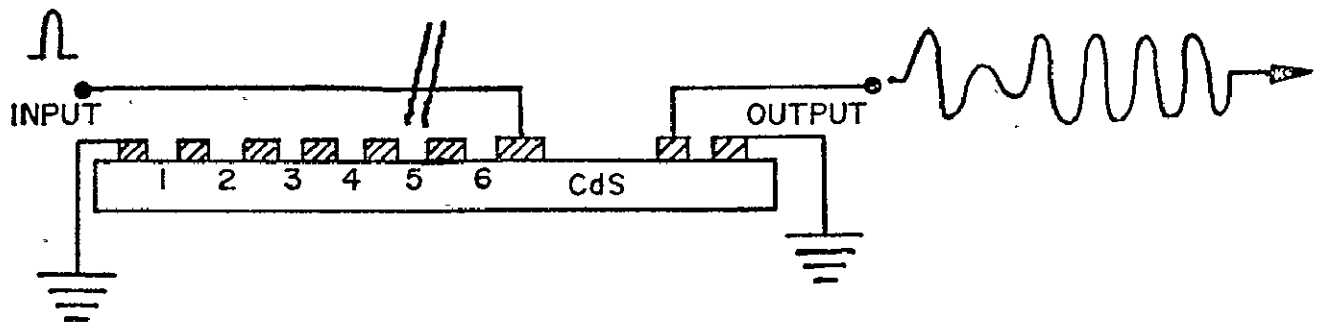


Figure 8. Scheme of using transducers in series. For illumination of the photoconducting material shunting transducer No. 5, the output signal should be as shown.

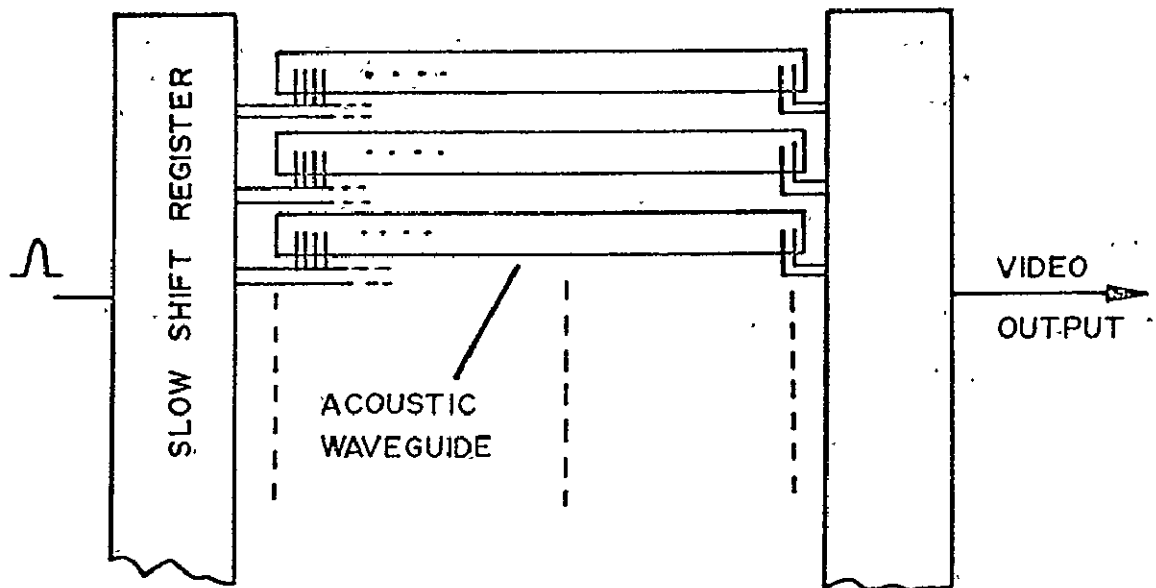


Figure 9. Two-dimensional sensor array composed of a series of adjacent acoustic waveguides.

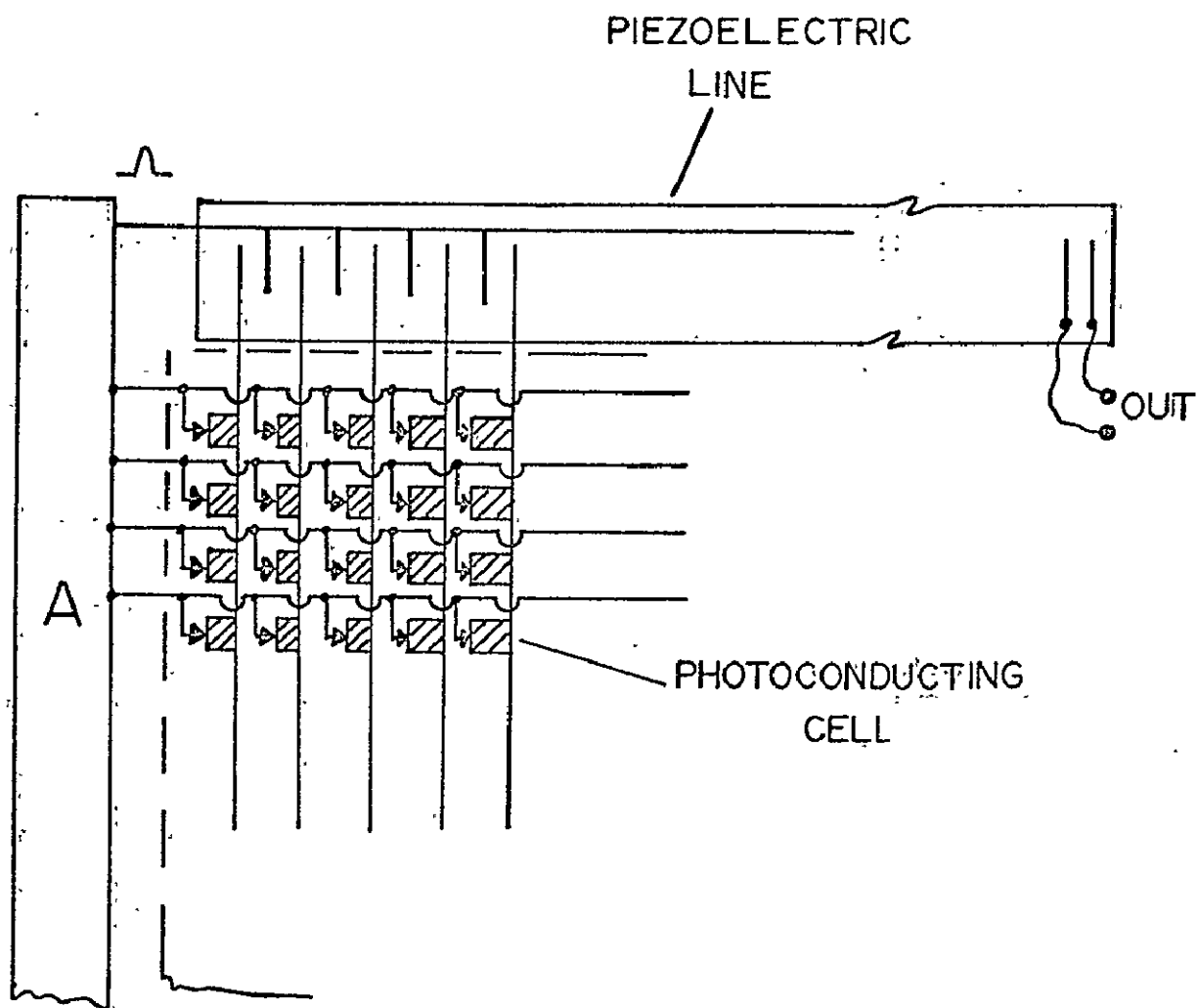


Figure 10. Two-dimensional "off-substrate" sensor array.

Initial attempts were made to investigate this scheme in the laboratory during the early part of the year, at a time when we could only fabricate low frequency transducers. The extraneous bulk waves generated in this low frequency system and the reflections of the surface waves caused this experiment to yield inconclusive results. It is planned to consider the problem again at a later time.

#### 4. Two-dimensional Arrays

We have been considering two different methods of extending the self-scanning technique that uses ultrasonic pulses to two dimensions. These are (a) miniature acoustic waveguides and (b) two dimensional off-substrate array technique .

##### (a) Acoustic Waveguides

The acoustic waveguide technique, illustrated in Figure 9, has each horizontal line as a self-contained system of evaporated piezoelectric surface wave transducers and photoconducting material. A slow vertical shift register excites each of these in turn, with the excitation time controlled by a clock pulse.

There are several methods by which ultrasonic waveguides can be fabricated. (Ref. 5.) The method that is probably most applicable here is the use of ridge guides, effected by a multiple-wire wire saw that cuts a large number of slots in a piezoelectric (quartz) plate. Recent reports indicate that a ridge can be an effective acoustic surface wave ridge guide even when its width is less than the acoustic wavelength. (Ref. 6.)

Experiments in our laboratory in which we have been investigating the fabrication of transducers on miniature acoustic waveguides are reported on page 33.

##### (b) Off-Substrate Arrays

This approach consists of having a single acoustic surface wave line perform the scanning function and switching the video elements exciting it. The video elements are necessarily separated from the acoustic line, hence the term "off-substrate array." Arrays for both the series and the shunt mode of operation are possible.

The basic scheme for an off-substrate two dimensional array is shown in Figure 10, where the series mode connection is shown, with sensing transducers used at the input.

In the operation of such an array, only one of the horizontal lines is connected by shift register A to the pulse source. When the pulse is applied to this line, the pulse voltages appearing across the various transducers of the piezoelectric line contain the information of the spatial illumination on the scanning elements of that line. These pulse

voltages then appear across the output transducer after being converted to information in elastic form and then reconverted to electrical form by the piezoelectric line.

Vertical scanning, i.e., switching from line to line, is accomplished by the vertical shift system.

The same two-dimensional array can be used for either the series mode or the shunt mode, since the only difference is the method of connecting the vertical lines to the acoustic array. This is shown in Figure 11 for a simple array of 16 photoconducting sensing elements.

It may be noted that diodes are required for isolation between photoconducting elements. These diodes could be fabricated simply by using a rectifying metal contact on the photoconducting material. If CdS is used for the latter, such a contact can be effected by evaporated tellurium.

The photoconducting elements are expected to be square patches of the order of several mils ( $\sim 0.1$  mm) on a side and of about one micron ( $1 \mu\text{m}$ ) thickness. They could be used either with parallel strip contacts on two opposite sides, or with a transparent contact (e.g., tin oxide) on top and the other contact on the bottom. In the former case the conductance and shunt capacity are much lower than in the latter. Calculations have been in progress to assess the relative merits of the two cases.

At this time, the technique of forming a two-dimensional sensing array by the method of off-substrate arrays appears preferable over the acoustic waveguide technique. We are, however, continuing work on both approaches until a definite conclusion can be reached.

## II. TECHNIQUES

Considerable time has been spent during this first year of effort at developing laboratory techniques for fabricating the various components of sensing arrays. Some of the efforts engaged in are described below:

### 1. Metal Deposition

Considerable efforts have been expended to develop satisfactory methods of controlled metal deposition. Among these have been the refurbishing of the pump and valve system of a vacuum evaporator; design, fabrication, and installation of proper shields, controls, and substrate heaters for evaporation; and the installation of an argon sputter-cleaning unit for substrate cleaning. Because of these changes, we are now able to deposit a number of metals in a controlled and satisfactory manner.

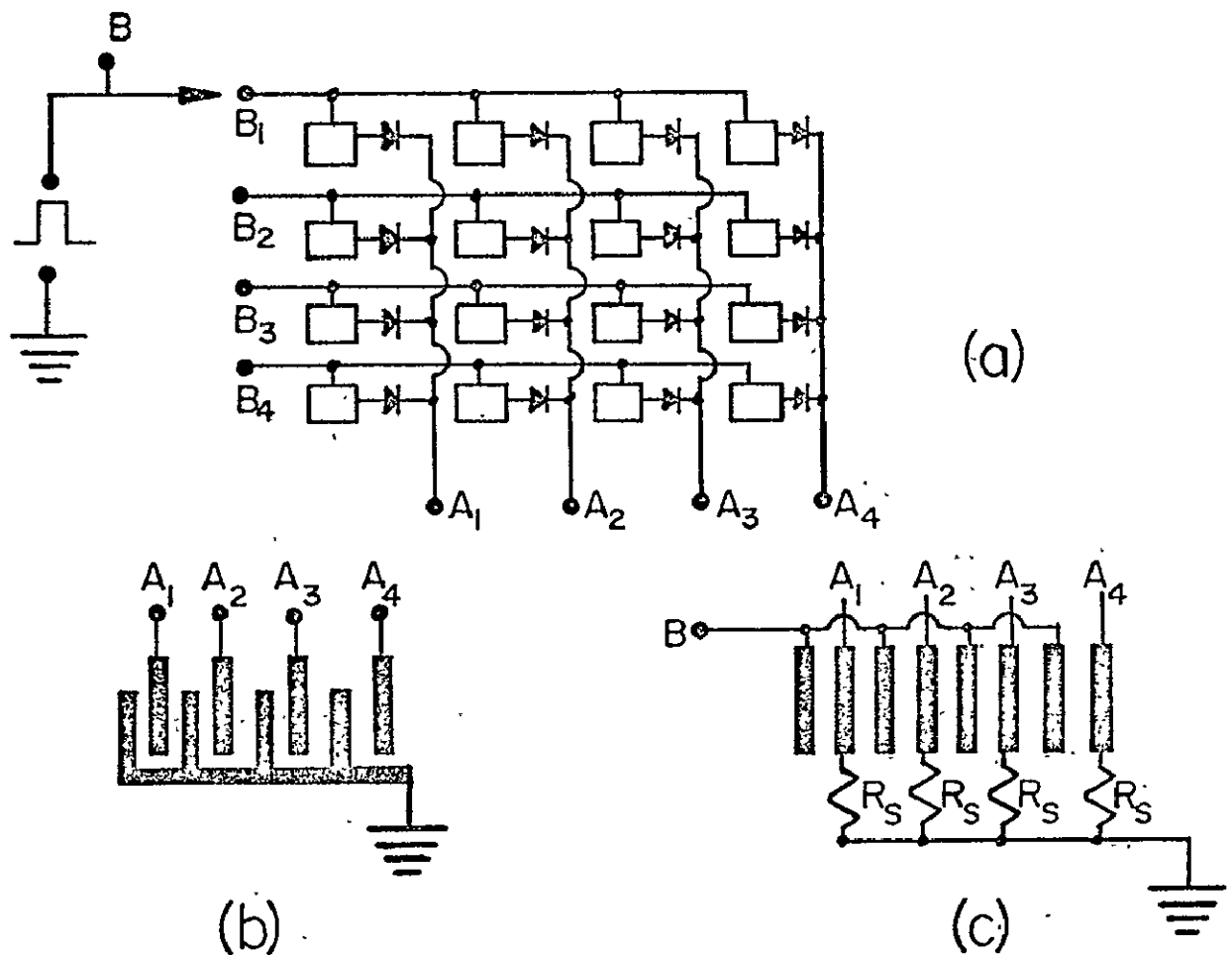


Figure 11. Two-dimensional "off-substrate" array.

- (a) The array of photoconducting elements.
- (b) Series connection. Here points  $A_1, A_2, A_3$  and  $A_4$  are connected to the corresponding points<sup>2</sup> of the array of photoconductors.
- (c) Shunt connection.  $B, A_1, A_2, A_3$  and  $A_4$  are connected to the corresponding points<sup>2</sup> of the array.

## 2. Photomasking/Selective Etching

At the start of this program we were only able to deposit acoustic stripe transducers through a slotted metal mask. This limited our capability for transducer fabrication to the low frequencies, i.e., to about 5 MHz or below. Since then, together with work on allied projects in the laboratory, we have been developing techniques of photomasking and selective etching that permit us to fabricate transducers suitable for much higher frequencies.

The technique here is the planar photofabrication technology, now used universally in the semiconductor industry, where a deposited metal film is covered with a photosensitive resist that is exposed by shining ultraviolet light through a negative of the desired transducer pattern.

The portions of the resist thus exposed are then removed by a suitable developing solution, leaving behind a pattern of resist corresponding to the desired pattern. The metal film is then immersed in a suitable etchant which removes the metal not protected by the resist. Then the resist is removed by a solvent, leaving the desired transducer.

In our work, a Kodak resist called KTFR was used with some acceptable results. It had several disadvantages, however. It was extremely difficult to remove without damaging the transducer and was susceptible to dust particles which degraded the resist pattern.

Later, AZ-1350, a resist by Shipley, was tried with much better results. Because it is a positive resist (KTFR is a negative resist), dust particles are less likely to degrade the pattern. In addition it is easily removed with acetone. The only disadvantage of this resist is that it is not resistant to base-type etchants like sodium hydroxide. In the case of aluminum, for which sodium hydroxide is normally used as an etchant, a phosphoric acid solution must be employed when using this resist.

Using the AZ-1350, transducers with line widths of one mil and one mil spacing, corresponding to a frequency of 30 MHz on alpha-quartz, have been successfully fabricated. Since such dimensions are those required for a video resolution of 250 elements per inch, the transducer fabrication process is now established.

## 3. Soldering/Wire Bonding

To make electrical connection to deposited acoustic stripe transducers on, say, quartz, we have used a soft-soldering technique developed in our laboratory. Here the quartz is placed on a hot plate, which is kept at a temperature somewhat below the melting point of the solder. A small piece of solder, which has been placed on the deposited silver stripe together with the wire to be bonded, is then heated by radiation (not by conductive contact) from a small hairpin hot wire.

The result is a good bond.

This technique has been used satisfactorily for our work to date. It will not be satisfactory, however, for a high resolution array system, where contact to 1 to 3 mil stripes must be made.

To make such fine contacts, we have recently acquired a Kulicke and Soffa Universal Wire/Die Bonder, as well as a smaller wire bonder. We expect to use these instruments for our precise work in the future.

#### 4. Ohmic Contacting

The problem of applying ohmic contacts to high resistivity materials is a well-known problem in semiconductor technology. We, also, encountered it this past year, when we tried to contact photoconducting CdS. It was found, for example, that evaporated silver contacts on ordinary CdS were not satisfactory. Some improvement was found after the surface of the CdS was slightly etched with 10% HCl, but a hysteresis effect in the I-V characteristics remained.

A more satisfactory method was the interposition of indium between the CdS and silver - though even this method was not completely satisfactory. It appears, therefore, that the problem of making completely satisfactory ohmic contacts to our photoconducting material requires some additional work.

#### 5. Miscellaneous

Such techniques as the deposition of photoconducting material, acoustic waveguiding, and shaping of the pulses supplied to the acoustic transducers are treated separately below.

### III. OPERATION OF SENSING ARRAYS

In the initial experimental demonstration of the use of acoustic pulses for self-scanned array sensing (page 12 ), the principle of operation was demonstrated by the functioning of one photoconducting cell. In order to demonstrate an array of a number of cells and to discover possibly hidden problems, several experiments with one dimensional arrays were performed.

#### 1. Slabs of Single Crystal CdS

An attempt was made to use two adjacent slabs of photoconducting CdS for the sensing of illumination on 12 adjacent stripes, using transducer stripes deposited on the CdS with center-to-center spacing of 1.5 mm (3 mm period).

The results obtained were:

- (a) In addition to exciting the desired surface-wave pulses, the applied voltage pulse also excited an unwanted elastic wave of approximately 300 kHz frequency. This wave was of high amplitude and made identification of the "wanted" pulses very difficult. Additional work showed that this disturbing wave was most likely a shock excitation of a transverse shear wave resonance of the slab.
- (b) Although the CdS slabs were transparent, they were not clear; so that appreciably light scattering appeared. This made it impossible to localize changes in resistivity due to localized illumination.
- (c) Great differences in photoconductivity were obtained, not only between the two slabs (which had been purchased to the same specifications), but also between different sections of the same slab.

## 2. CdS Bars

To reduce the difficulties due to light scattering and those due to the acoustic resonances of the thin CdS slabs, an experiment was performed with Y-cut alpha-quartz as the piezoelectric medium and CdS bars as the photoconducting medium. As in the previous experiment, the parallel mode of operation was used. The sending array was constructed of 15 pairs of 3 MHz transducers (1 mm period). Each transducer was connected in series with a  $10^5$ -ohm resistor to the pulse generator and had a bar of CdS placed across it. (See Figure 12.)

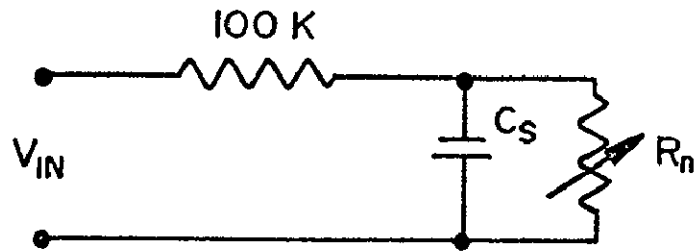
The input was a 100-volt pulse of 0.16 microsecond duration and a 1 kHz repetition rate. The output was observed on a CRO with input impedance of  $10^6$  ohms, shunted by 15 pfd.

Identifying the input transducers by number as they occurred in sequence in the direction pointing away from the output transducer, the following transpired: In attaching the leads to the transducers, #2, and #4 were open circuited. The CdS bars were placed on the transducers #3, and #5 through #13 and contact was made using an indium-gallium alloy painted on the transducer electrodes. Due to contacting problems, only transducers #5, #6, #7, #8 and #3 showed any appreciable photo-sensitivity. In the resulting oscilloscope traces, seen in Figure 13, the top trace is the output for the array in darkness. The center trace is the output with the array fully illuminated with  $\approx 300$  ft-candle light from a microscope illuminator. In the bottom trace, the output is for the case when only transducer #8 was illuminated.

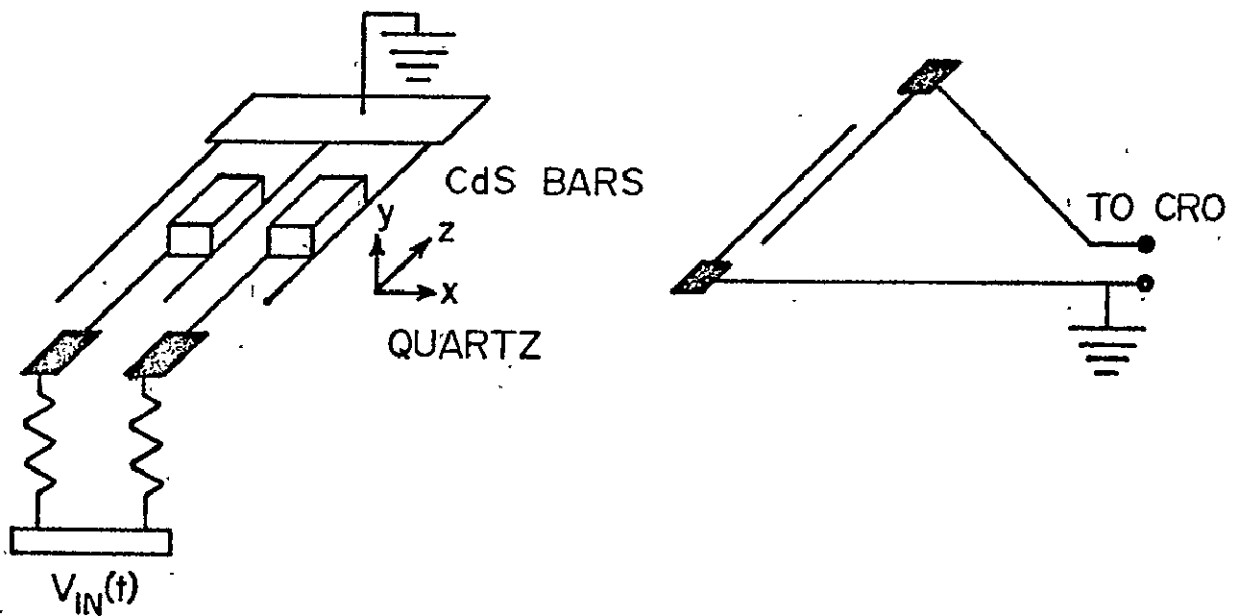
The following conclusions could be drawn:

- (a) Use of the shorter pulses, corresponding to 3 MHz transducers, and of the thicker quartz (instead of the thin CdS slab) reduced the disturbing shear wave resonance enormously.





-a-

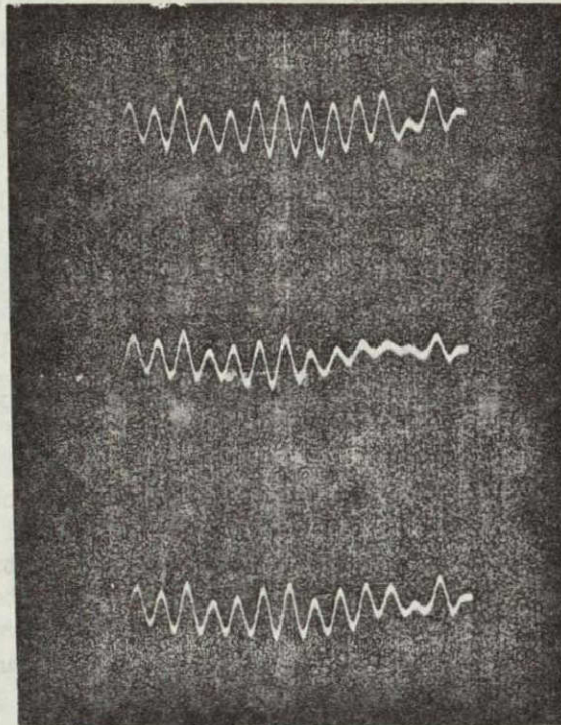


-b-

Figure 12. Operation of an array of acoustic transducers shunted by photoconducting CdS bars.  $C_S$  is the pair capacitance:  $R_\lambda$  is the photoresistance.

(a) Equivalent circuit of one element.

(b) Experimental arrangement.



↑  
NO. 8

Figure 13. Output signal for half-sine wave pulse input to CdS bar array. Top: Array in darkness. Center: Array fully illuminated. Bottom: Illumination only on transducer No. 8; the others in darkness.



(b) For the first time, sensing of the photoconductivity of more than one location occurred.

(c) Serious problems in ohmic contacting were still present.

### 3. Discrete Photoconductors

An excellent demonstration of the self-scanning photosensing system was seen when discrete photoresistors were substituted for the integrated photoconductors (of the ultimate system). The arrangement used was that of Figure 14; the results are given in Figure 15. A photograph of the array system is seen in Figure 16.

As seen in Figure 14, several photoconducting cells were connected in the series mode to the piezoelectric surface wave transducer array. The assembly was pulsed with half-sine-wave pulses.

The resulting voltages existing across the "out" terminal, for different distributions of illumination, are shown in Figure 15. Here it is seen that the amplitude pattern of the various pulses is indeed the pattern of the distribution of the illumination of the array.

While some work will be required to eliminate such minor disturbing features as the slowrise in the dc level and the small output pulses that occurred when the array was in darkness, in addition to the larger problem of finding the correct photoconductors and integrating the array, the displays of Figure 15 definitely show the validity of the technique of using a piezoelectric system of self-scanning of an optical sensor array.

### 4. Photodiodes

Although it appears most desirable to use photoconducting material as the sensing material, because of the simplicity of deposition, it is of interest to see if photodiodes could offer improvements. To this end, a brief investigation of the use of photodiodes was made.

A simple analysis indicated that their use might be feasible. A prototype model using PZT-8 as a substrate for the transducer and LS400 photo-duo-diodes for video elements was therefore assembled in the laboratory and tested, with positive results. With this encouragement, a more detailed circuit analysis is now in progress.

The circuit used, shown in Figure 17, consists of a ten pair transducer with the LS 400s connected to the pairs numbered 1, 2, 3, 4, 5, 7 and 8. The other three pairs were damaged during assembly. The operating frequency of the transducer was at 6.72 MHz.

The oscilloscope traces of Figure 18 illustrate the output of the array under various light conditions. Because the photodiodes used had lenses attached to them, it was very difficult to illuminate all of them



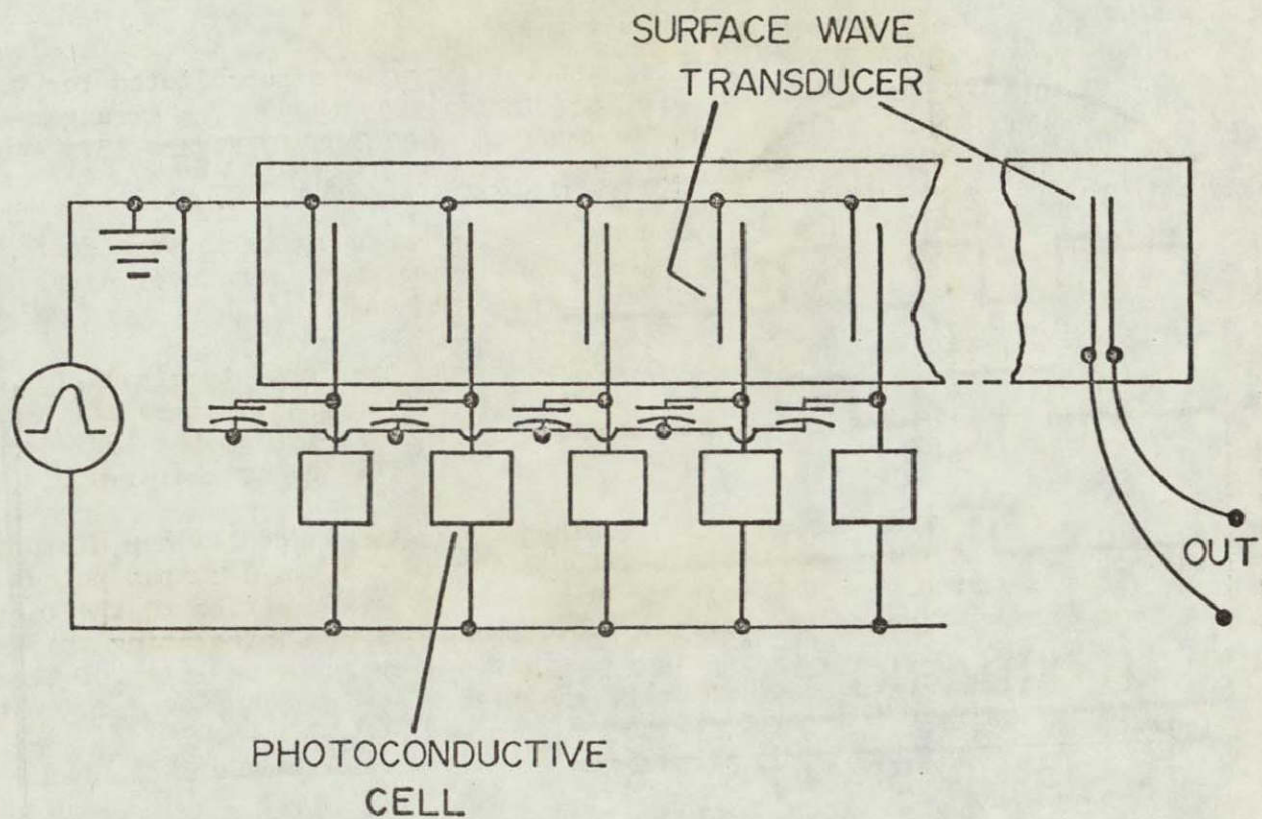


Figure 14. Sensor array composed of discrete photoconductors and acoustic surface wave transducers. The actual array consisted of nine active elements.

LIGHT :

OUTPUT :

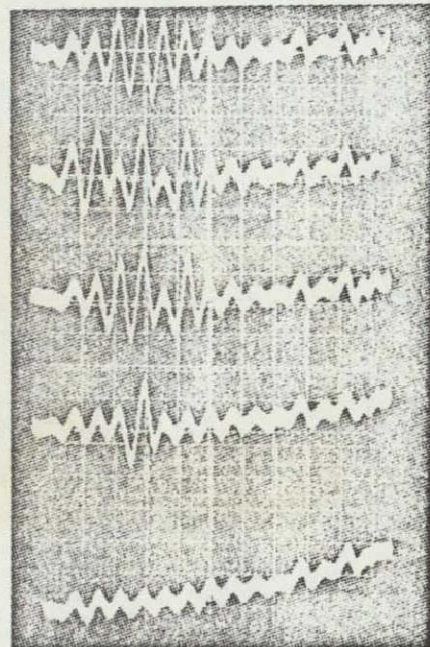
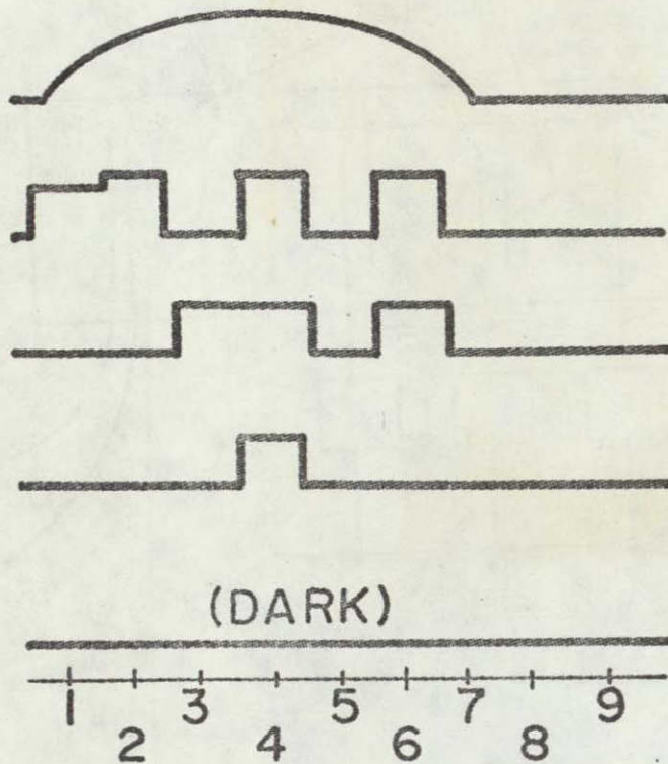


Figure 15. Output signals obtained (right) for various patterns of illumination applied to the nine photosensors.



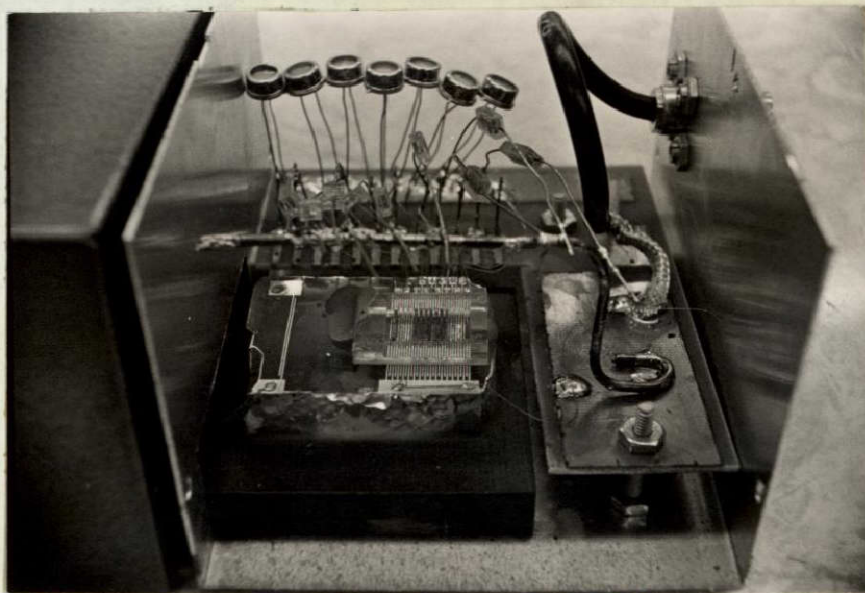


Figure 10. Photograph of sensor array pictured schematically in Figure 14.

NOT REPRODUCIBLE



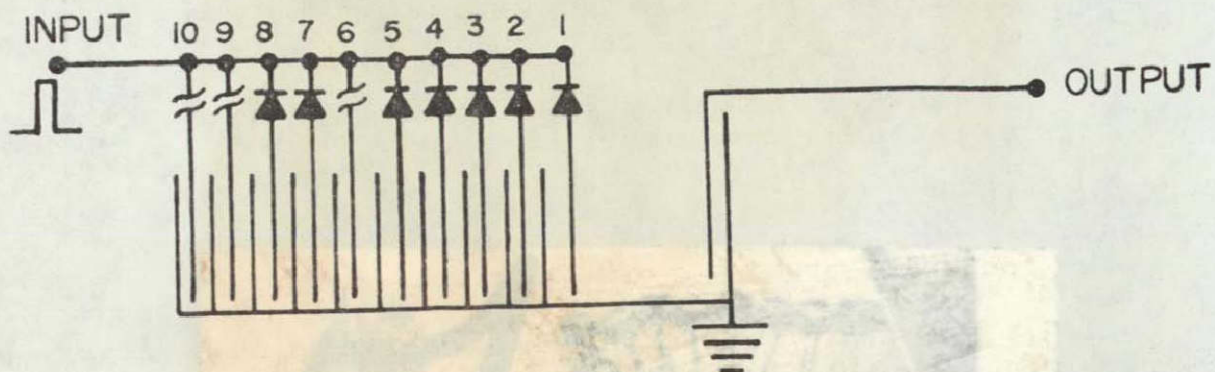


Figure 17. Sensor array using photodiodes and acoustic surface wave transducer array.

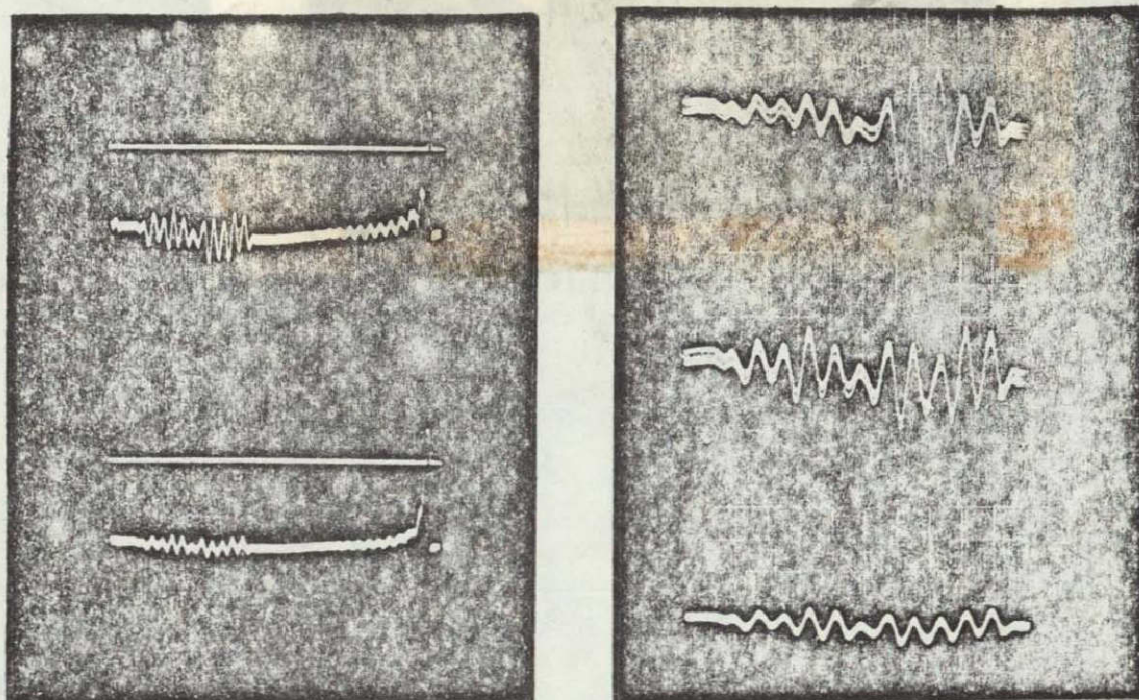


Figure 18. Input and output signals for photodiode array. Left: Upper frame has input and output signals for all elements illuminated; lower frame for all in darkness. Time base is 0.5 microsecond/cm. Upper traces are input signals, @ 20 volts/cm; lower traces are output signals, @ 20 millivolts/cm. Right: Upper trace is output with units No. 3 and 4 illuminated; center with all elements illuminated; lower with all elements in darkness. Time base is 0.2 microseconds/cm. Sensitivity is 10 millivolts/cm. In all cases, time is from right to left.



uniformly at the same time, since the lenses made the diodes very sensitive to the direction of the incident light.

If this anomaly is discounted, it can be seen that photodiodes, also, could be used in a sensing array.

#### IV. ACOUSTICS

##### 1. Transducer Fabrication and Operation

The fabrication of acoustic transducers has already been discussed on p. 23 . We are now able to fabricate interdigital transducers for frequencies up to 30 MHz.

The scheme proposed for self-scanning uses half-sine-wave voltage signals for pulsing the transducers. Because of the fact that piezoelectric transducers are not of unlimited bandwidth, it was fortuitous that these half-sine-waves could pass through the piezoelectric conversion system without appreciable change of waveform. (See, for example, Figure 15.) There is at this time no assurance, however, that this situation will still exist for a line of, say, 250 elements, since the paralleling of these elements could change the balance of effective resistance to reactance. We have therefore started to investigate the circuit aspects of this problem, as discussed in Section VI, below.

Other considerations involve the reflections and loss from using a piezoelectric line loaded with many transducers and photoconducting material. This aspect of the problem, also, is presently under investigation - both theoretically and experimentally.

##### 2. Acoustic Waveguiding

Experiments are in progress to determine the feasibility of the technique of constructing a sensing plate composed of a number of acoustic waveguides, as in Figure 9. The problem here is not solely to propagate MHz acoustic waves along a waveguide, for this has been accomplished (Ref. 5), but to find suitable means of exciting these waves.

Here several possibilities exist. In the most obvious technique, miniature transducers are evaporated directly on each guide.

At the present time, we have evaporated transducers whose initial beam width is 0.4 mm and received satisfactory transmission. A photograph of such a 10 MHz transducer on single crystal quartz is shown in Figure 19. Input and output voltage pulses for four-pair transducers are shown in Figure 20, where it is seen that with a 60 V. peak-to-peak input a visible output signal is readily obtainable. Because of the high impedance of such small transducers, the amount of power involved is extremely small, so that a very low power drive system could be used. Moreover, we note from Figure 19 that we did not actually have a narrow waveguide to trap the radiation in this experiment. The use of such a narrow guide



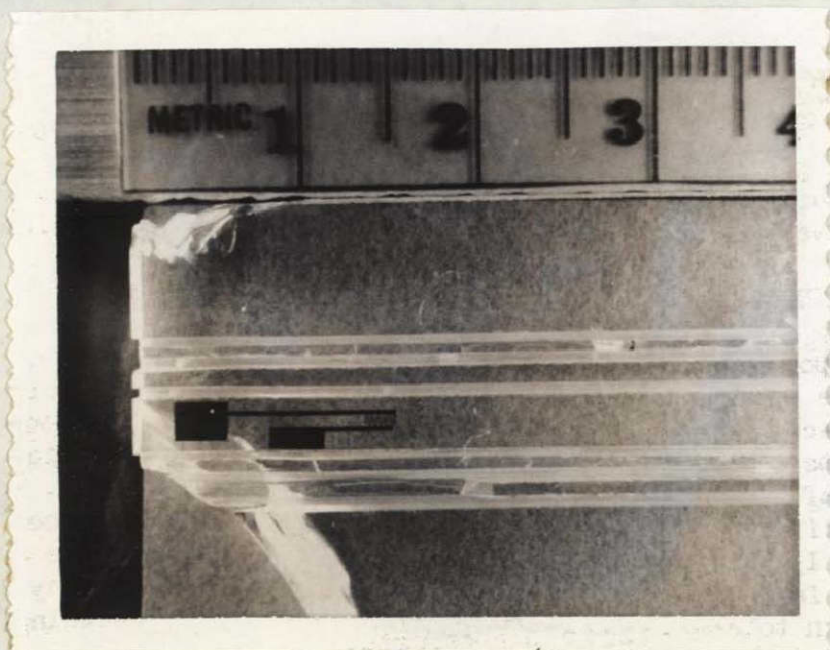
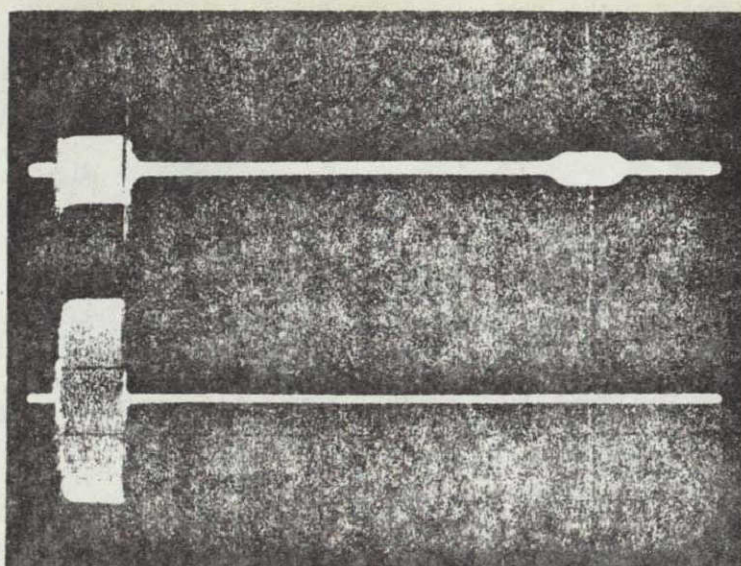


Figure 19. Photograph of 10 MHz transducer on single crystal quartz, with initial beam width of 0.4 mm.



NOT REPRODUCIBLE

Figure 20. Response of narrow-width transducers of Figure 19 to 10 MHz tone bursts. Bottom: Input. Top: Output. The wavetrain on the left of the top trace is due to electrostatic pickup.

is expected to increase the ratio of output to input voltage.

We are presently preparing to deposit transducers on a 0.125 mm ridge of quartz in our continued investigation of the feasibility of acoustic waveguiding.

## V. PHOTOCONDUCTIVE MATERIAL

The deposition of photoconducting material of the correct resistivity and time response, and the technique of making ohmic contacts, are important facets of the photosensor problem. We have started on this work by depositing CdS photoconducting films from a slurry. Although some films of reasonably low resistivity (in light) have been made, we have had difficulties in making these films repeatably. We are therefore presently performing a library search to obtain as many recipes as possible of fabricating photoconductive films before deciding on specific ones on which to concentrate our efforts.

The problem of finding the correct photoconductor can be divided into two steps:

1. Depositing and ohmic-contacting a photoconductor of the desired resistivity and sensitivity.

2. Tailoring of the time response.

From the considerations of providing a film that, when illuminated, has a lower resistance than the reactance shunting it (see page 7) we desire a photoconductor that can fulfill this criterion when in thin film form. To permit the frame rates required for viewing motion, we need a material whose time response is of the order of a few milliseconds.

It was an obvious decision to concentrate our initial efforts on the fulfilling of the first criterion.

To start this work, we attempted to contact, with the aid of our technical monitor, a number of industrial concerns that have been fabricating photoconductors. Regrettably, the detailed recipes for deposition in many cases were found to be of industrial proprietary information; so that we were unsuccessful with this approach.

A number of methods of depositing CdS are indexed in Chemical Abstracts. Unfortunately, a number of these have been found too sketchy to result in satisfactory films without considerable experimentation. We therefore used a method given by Matsushita Electric Industrial Co. that listed sufficient details to encourage a start. After some experimentation, the following "best recipe" to date contained a mixture of 5.3 g  $\text{Cd}(\text{NO}_3)_2$ , 16.7 g Thiourea, 120 cc 28%  $\text{NH}_3$ , 10 cc 1M  $\text{CdCl}_2$ , and 645 cc distilled water. When this mixture was heated to boil, deposition of CdS on a glass slide occurred. Following a suggestion by

Mr. N. G. Sakiotis of this Laboratory, this CdS was made photoconductive by heating the coated slide on a strip heater in a nitrogen atmosphere for 30 to 60 minutes. The "best slide" prepared in this manner exhibited changes in resistance under varying illumination of three orders of magnitude. Its sheet resistance when illuminated by a microscope illuminator was approximately  $10^5$  ohms per square, corresponding to a resistivity of the order of 10 ohm-centimeters.\*

Unfortunately, we have been unable to repeat these "best" results. It is planned to resume this work this coming year by assigning a graduate student solely to this aspect of the problem in order to: a) become well acquainted with photoconductive phenomena, b) continue the method of deposition from slurries, c) utilize techniques of vacuum deposition presently under investigation in the Laboratory by Mr. N. G. Sakiotis (in connection with another program).

## VI. CIRCUITS

Work has been in progress on the circuit considerations involved in the self-scanning array sensor. These deal both with arriving at optimum configurations of the sensor array and with auxiliary circuits. Examples are given below.

### 1. Requirement on Photoconductivity for Off-Substrate Array

We consider a patch of photoconducting material of dimensions 0.002 " X 0.002 " ( $5 \times 10^{-2}$  mm X  $5 \times 10^{-2}$  mm) and of thickness 5 microns, with ohmic (transparent) contacts on top and bottom of the square. This patch will become a useful photoconductor if the resistance in the dark is very high and the resistance in light is of the order of or smaller than its shunt reactance. For CdS, with a dielectric constant of 10, the capacity of this patch is

$$C = \frac{(8.854)(10^{-12})(10) [(5)(10^{-5})]^2}{(5)(10^{-6})} \quad \text{farads.}$$

$$= (4.4)(10^{-14}) \text{ f.}$$

At 50 MHz, the shunt reactance is therefore  $(7.2)(10^4)$  ohms.

If we want the resistance to be of the same amount (in light), we require the CdS to have a resistivity given by

$$\rho = RA/l = 36 \text{ ohm-m} = 3600 \text{ ohm-cm.}$$

\*Exact figures could not be determined, since at that time the Laboratory possessed no means of measuring film thickness. We now possess an interferometric microscope for performing this measurement.

Using the approximation made in the early part of the report, we find:

Required carrier density  $n = \rho^{-1}/\mu q = (1.8)(10^{18})$  electrons/cm<sup>3</sup>, where a mobility of 0.1 m<sup>2</sup>/volt-sec has been assumed.

The carrier density per unit area is therefore

$$n_s = (n)(5)(10^{-6}) = (9)(10^{12}) \text{ electrons/m}^2.$$

For a quantum efficiency of 10% and a lifetime of  $10^{-2}$  seconds, the optical power density of 6000 Angstrom radiation required to maintain this density is  $(3)(10^{-7})$  watts/cm<sup>2</sup>. This is two to three orders of magnitude below the light level available from an overcast sky passed through an f/2 lens. The off-substrate photoconductive patch technique therefore appears as a feasible method, when examined from the viewpoint of available photoconductivity.

It is of interest to compare this result with the photoconductivity existing in a commercial photo cell. A Clairex Type CL705HL, composed of CdS, is rated as having a resistance of 50,000 ohms in 1 ft-candle illumination; of 400 ohms in 200 ft-candles. According to its dimensions of 45 mm X 0.2 mm X 10  $\mu$ m (estimated), its resistivity in 100 ft-candles is 90 ohm-centimeters. The rise and fall times for this resistivity are 5 and 2 milliseconds, respectively.

Since an overcast sky ( $\sim 10^3$  foot lamberts) focused through an f/2 lens causes an illuminance in the image plane of  $E' = \pi B/4F^2$  foot-candles (Ref. 2), this here is 196 foot-candles. As a result, for the material of this photo cell, whose response time is sufficiently fast, the resistivity is as low as 90 ohm-centimeters. This compares very favorable with the requirement set by the circuit that the resistivity of the photoconducting material should be somewhat below 3600 ohm-cm for that light intensity.

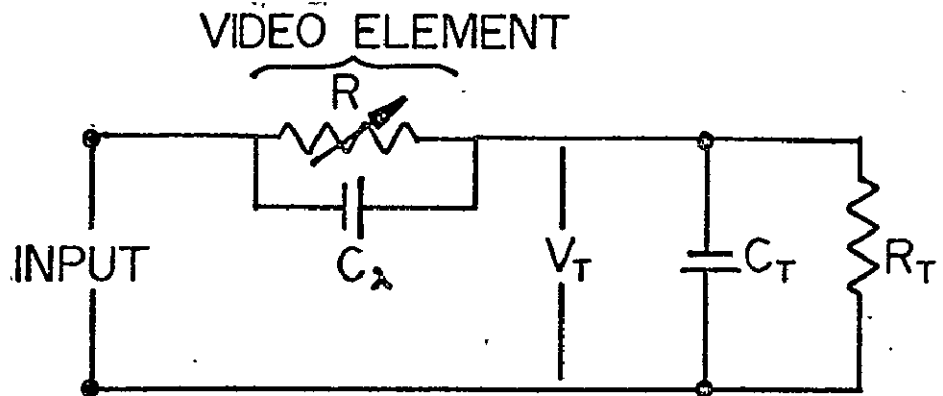
We conclude that photoconductive materials of sensitivity and response times required for the off-substrate self-scanning array are feasible.

## 2. Choice of Parameters and Configurations

We are presently in the midst of analyses in which we are trying to determine optimum parameters and configurations that keep the piezoelectric line from being loaded by the photoconducting elements, while at the same time maximizing the video signals that are due to the spatial variations in illumination.

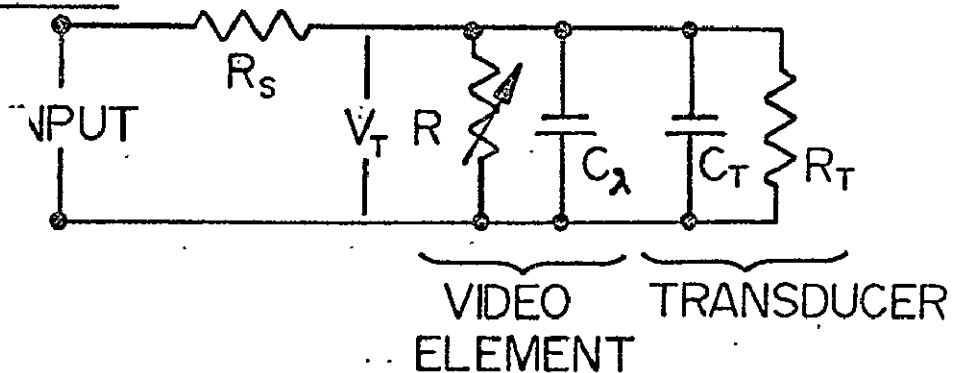
A portion of this problem is illustrated in Figure 21, for both the series and shunt modes. The problem here is to find optimum values that can be achieved in practice for the various parameters shown, in order to result in the largest video signals.

## SERIES MODE:



$$|V_T| = V_{\text{INPUT}} \cdot \frac{\left[ R_\lambda^4 (\omega^4 R_T^4 C_\lambda^2 (C_\lambda + C_T)^2 + \omega^2 R_T^2 C_\lambda^2) + R_\lambda^3 (2\omega^2 R_T^3 C_\lambda^2) + R_\lambda^2 (2\omega^2 R_T^4 C_\lambda (C_\lambda + C_T) + R_T^2 + \omega^2 R_T^4 C_T^2) + R_\lambda (2R_T^3) + R_T^4 \right]^{1/2}}{\left[ R_\lambda^2 (1 + \omega^2 R_T^2 (C_\lambda + C_T)^2) + R_\lambda (2R_T) + R_T^2 \right]^{1/2}}$$

## SHUNT MODE:



$$|V_T| = V_{\text{INPUT}} \cdot \frac{1}{\left[ \left( 1 + \frac{R_S}{R_T} + \frac{R_S}{R_\lambda} \right)^2 + \omega^2 R_S^2 (C_\lambda + C_T)^2 \right]^{1/2}}$$

Figure 21.  $V_T/V_{\text{INPUT}}$  for series and shunt modes.

This problem is now being solved by programming of the analytical expressions of Figure 21 on a computer and running numerical analyses.

Examples are given in Figure 22 and 23, which show the transducer voltages developed for fixed (pulse) supply voltage and a range of resistance  $R_\lambda$  of the photoconductor at 35 MHz.\*

In the off-substrate array, with square patches of photoconducting material, there is the choice of ohmic-contacting these patches on top and bottom of the squares (Case 1) or on each of the two sides of each of the squares (Case 2). The two cases yield different answers for the video signal, i.e., the difference in transducer voltage  $V_T$  for illuminated and dark conditions.

For the conditions corresponding to the plots of Figures 22 and 23, which are for square sensing elements 1 micron thick, and with a linear density of 100 elements per cm, with alpha-quartz as the associated piezoelectric material, and with transducers 1 cm long, values obtained for the desired resistivities are given in Table 3.

TABLE III  
Optimum Resistivities (ohm-centimeters) of Photoconducting  
Material in Average Light

	Case 1	Case 2
Series Mode	55.5	0.12
Shunt Mode	36	0.07

Clearly, the values for Case 2 shown here are much too low; those for Case 1 may be satisfactory.

It is through plots of this nature, with varying geometries, that optimum values are presently being searched for.

As stated above, in addition to the problem of the simple element, we are presently also considering the effect of loading of all the other elements on one that is actively receiving. In addition to calculations, this also involves some experimental determination of piezoelectric parameters, a procedure also presently in progress.

\*The curves of Figure 22 and 23 are for the sine wave case. This will be applicable if pulse trains are used for excitation. While half-sine-wave excitation requires a pulse analysis, the sine wave analysis is a good guide.

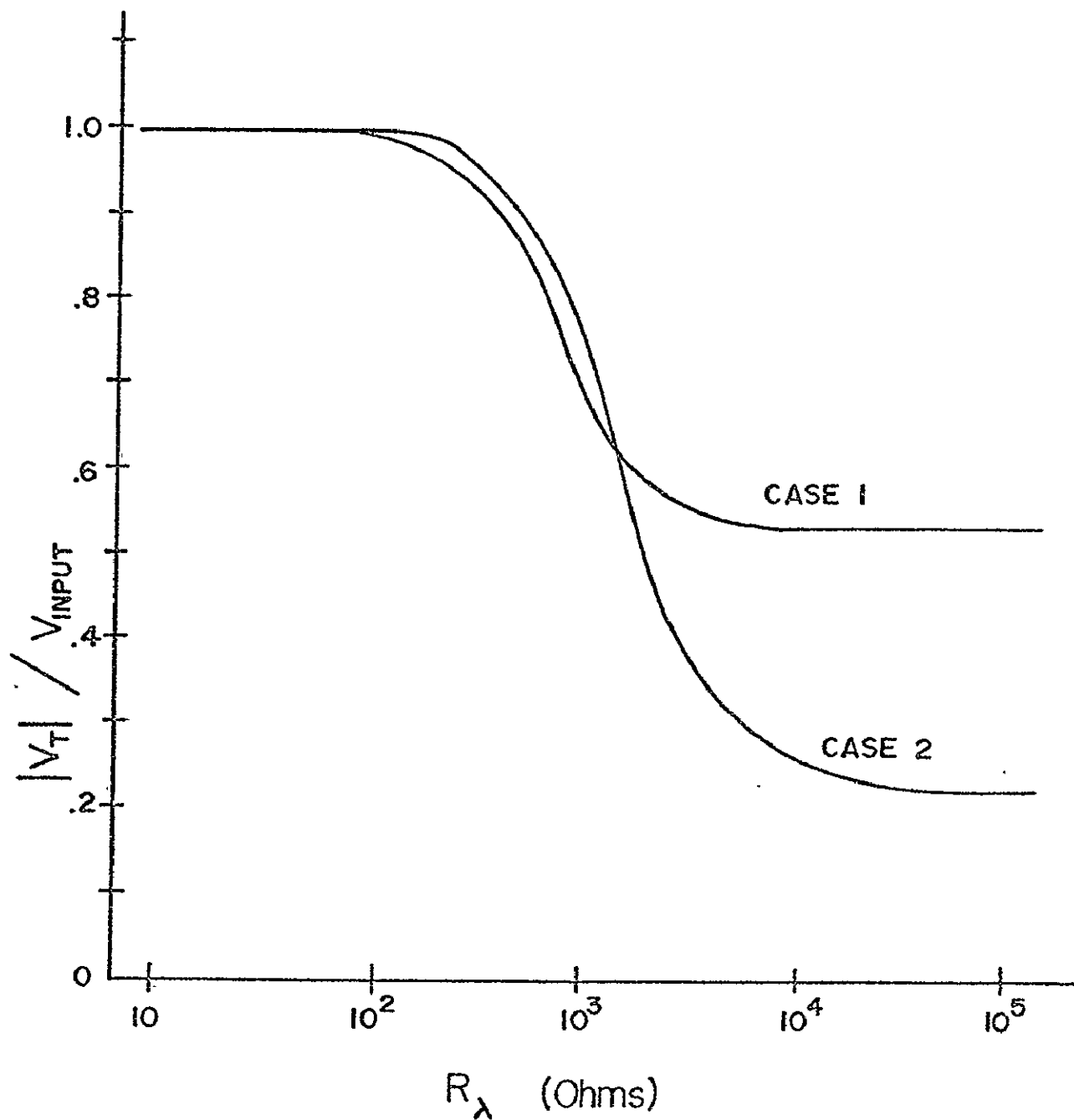


Figure 22.  $V_T/V_{INPUT}$  vs  $R_\lambda$  for series mode operation.

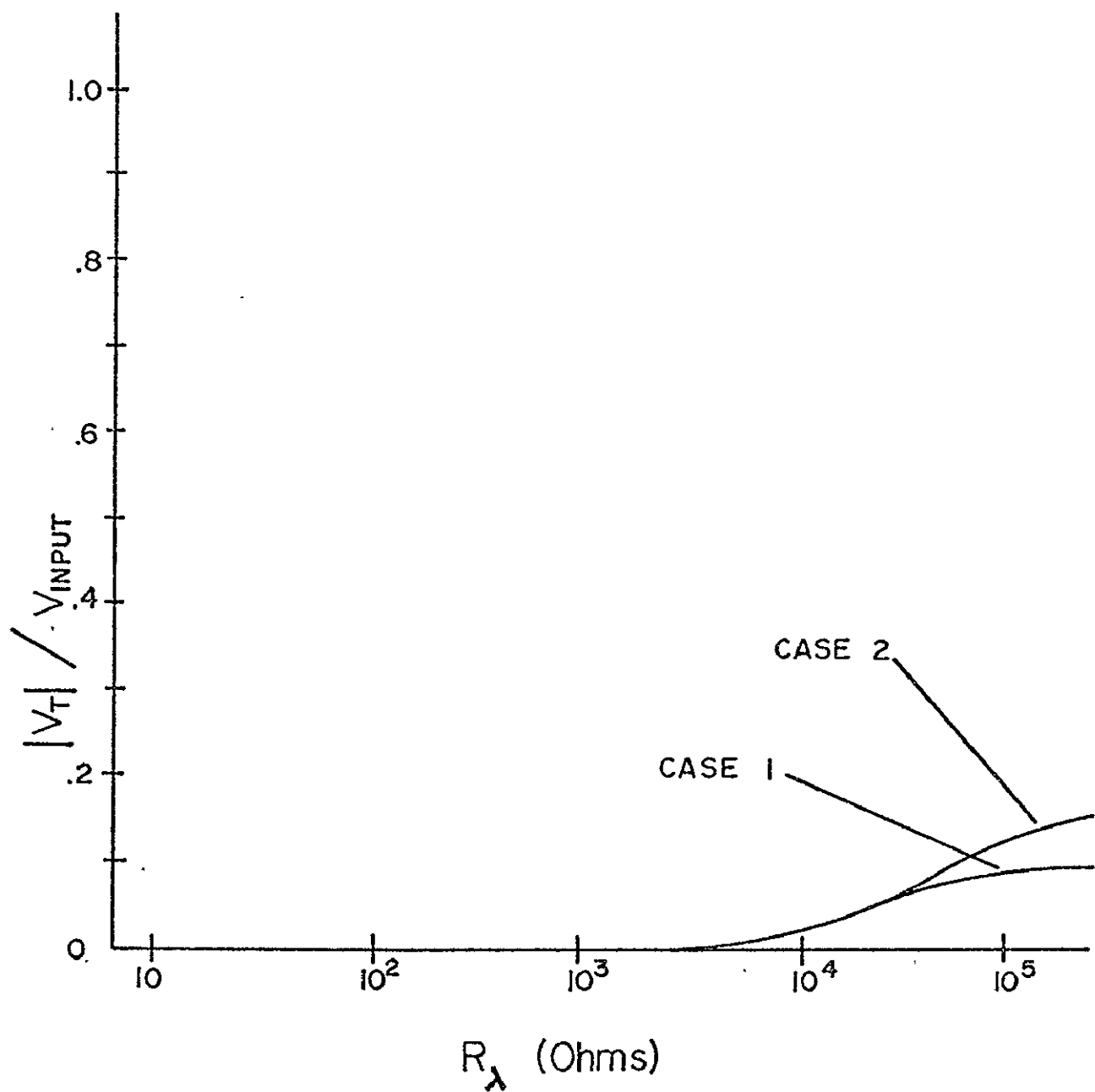


Figure 23.  $V_T/V_{INPUT}$  vs.  $R_\lambda$  for shunt mode operation.



### 3. Auxiliary Circuits

Two examples of auxiliary circuits are a tone pulser that has been constructed and detection circuitry that is under consideration.

#### a) Tone Pulser

In order to provide tone bursts of one to several cycles at a repetitive rate for testing arrays, a simple electronic switch was designed and constructed. Basically, its use is as illustrated by the block diagram of Figure 24(a).

The circuit for the tone pulser is illustrated in Figure 24(b). Here diodes should have a fast response and low shunt capacitance. The inductors provide a path for the DC bias current while presenting a sufficient impedance to the RF signal. The capacitors at the input and output ports isolate the signal source and the load from the DC bias current. The capacitor to ground between the two diodes add additional attenuation of the signal during periods of no desired output.

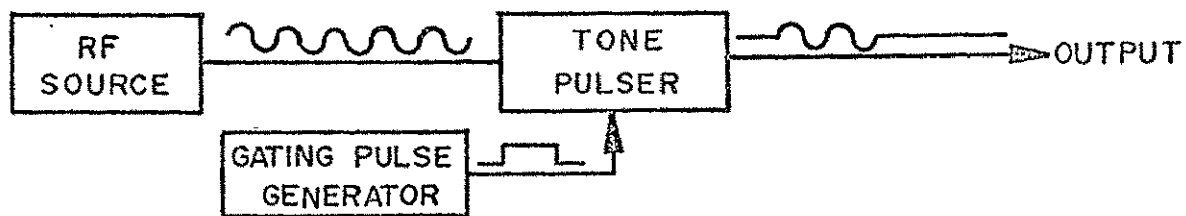
The values of L and C are selected for the desired Q at the desired signal frequency and load or source impedance. A Q less than 10 is recommended, since a high Q will result in undesirable transients due to the pulse storing energy in the inductor and capacitor. The DC bias voltage must be greater than the peak value of the RF signal and the gating pulse amplitude must be greater than the peak-to-peak value of the RF signal.

For the specific tone pulser that has been built in the laboratory, the RF signal frequency is 10MHz, the load and source impedances are 50 ohms, and the peak-to-peak value of the RF signal is 20 volts. A value  $Q=1$  was used, giving values for the inductors of one microhenry and for the capacitors of 330 picofarads. The center capacitance is 16 picofarads and the diodes are FD700s. The DC bias voltage is 22.5 volts and the gating pulse amplitude is 35 volts. The completed pulser has an output bandwidth from 7.5 to 17 MHz, and an ON to OFF amplitude ratio greater than 40 db.

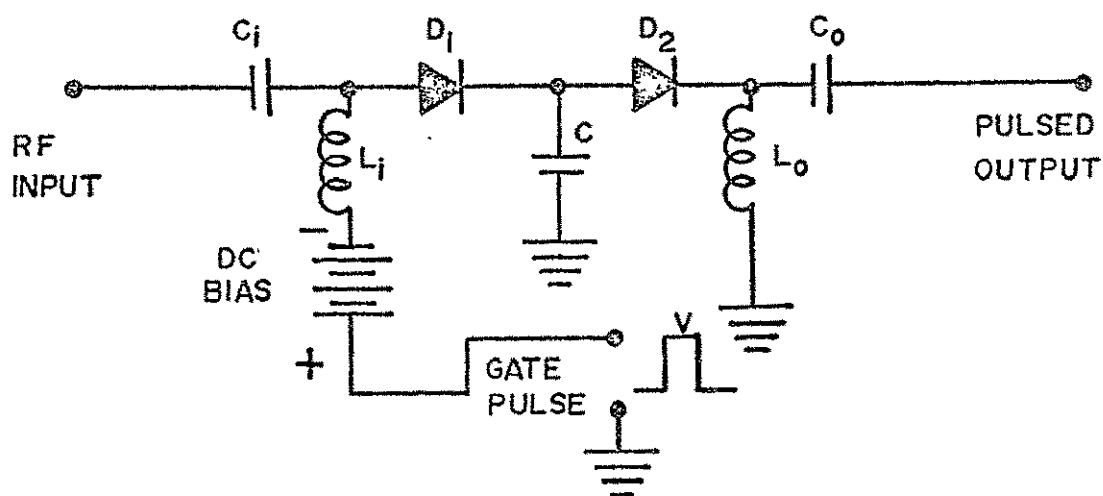
#### b) Video Detection

The method of recovering the video information from the output waveform was investigated, with the following conclusions. The output waveform is a sinusoidal wave at the transducer's resonant frequency which is amplitude-modulated by the video signal. The highest modulation frequency occurs when the video elements are alternately illuminated and dark. This frequency is equal to the transducer's resonant frequency, or carrier frequency, divided by twice the number of transducer pairs per video element.

To employ a simple diode detector requires that the highest modulation frequency be less than one fifth the carrier frequency. This type



(a)



(b)

Figure 24. Tone Pulser.

(a) Block diagram.

(b) Circuit of pulser used in laboratory.

of detector would therefore require that three transducer pairs be used for each video element. Thus, for an array of  $25^4$  video elements per inch, 762 transducer pairs per inch would be required. This corresponds to an operating frequency of 189.24 MHz when alpha-quartz is used for the substrate. Because of the high operating frequency required, transducer fabrication would be difficult and the propagation loss would be much higher. Therefore, a simple diode detector is not considered to be the best approach for recovering the video information.

More complex detectors are available that would permit the use of only one transducer pair per video element. For the case illustrated above, this would permit an operating frequency of 31.54 MHz on alpha-quartz. An example of one such detection circuit is illustrated in Figure 25, neglecting the necessary bias voltages.

The output of FET 2 is controlled by the voltage to which C is charged. FET 1 is turned on and off at the peak of each cycle of the input waveform by the sampling gate pulse. This switching action allows C to charge or discharge to the peak amplitude of each succeeding cycle of the input signal. Thus the output voltage of FET 2 across  $R_L$  corresponds to the video signal modulating the input signal. R is present to provide a discharge path for C, and the diode removes the unwanted negative portion of the input signal. The product of R and C must be less than  $\frac{1}{4}$  the width of the sampling gate pulse which in turn must be less than  $\frac{1}{8}$  of the duration of a single input cycle.

For example, with a 31.54 MHz input signal, the sampling gate pulse width would be 4 nanoseconds and for a C of 10 picofarads, R would be 100 ohms.

#### SUMMARY AND PLANS

During this first year of the investigation of a scheme that uses acoustic surface wave pulses for self-scanning of an optical array sensor we have demonstrated the principle of operation in several experiments; have made a great deal of progress in developing techniques aimed at the construction of such sensors; have proposed improved and two-dimensional configurations; have initiated deposition of photoconducting elements; and have become involved in the design consideration.

The work that follows will continue the design studies, the work on photoconductors and ohmic contacting, and the studies on acoustic waveguiding. We expect to construct an optical system for testing an array sensor. And we expect to combine the various facets in the construction of operating array sensors.

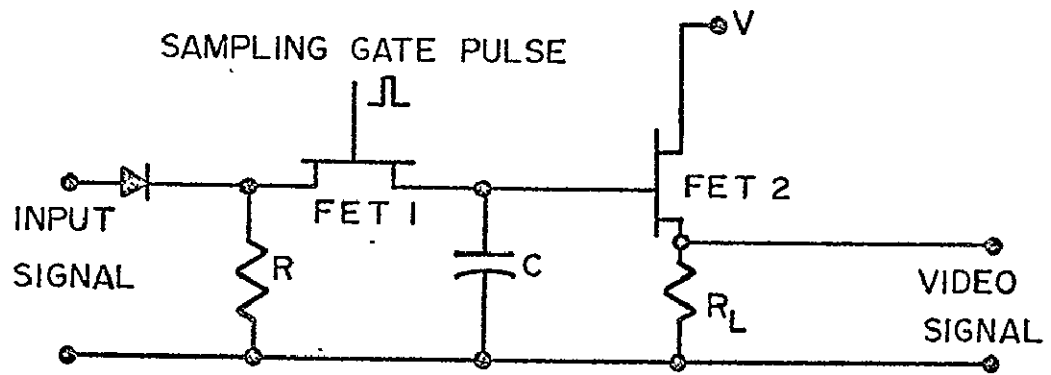


Figure 25. Possible detection circuit to be used following output transducer.

#### REFERENCES

1. P. K. Weimer, W. S. Pike, G. Sadasiv, F. V. Shallcross, and L. Meroy-Horvath, "Multielement Self-Scanned Mosaic Sensors." IEEE Spectrum, March 1969, pp. 52-65.
2. D. G. Fink, Television Engineering Handbook, McGraw-Hill, 1957, p. 3-41.
3. D. G. Fink, op. cit., p. 3-21.
4. R. M. Arzt, E. Salzmann, and K. Dransfeld, "Elastic Surface Waves in Quartz at 316 MHz." Appl. Phys. Lett., Vol. 10, 1 March 1967, pp. 165-167.
5. E. A. Ash, R. M. DeLaRue, and R. F. Humphryes, "Microsound Surface Waveguides." IEEE Trans. on Microwave Theory and Techniques, Vol. MTT-17, Nov. 1969, pp. 882-892.
6. R. M. DeLaRue, R. Humphryes, I. Mason, and E. A. Ash, "Optical Heterodyne Observation of Guided Wave Propagation." International Symposium on Acoustic Surface Waves. IBM, Yorktown Heights, N.Y., March 1970.

## PERSONNEL

Dr. I. Kaufman	Principal Investigator
Mr. K. A. Shaw	Graduate Research Assistant/Associate
Mr. J. F. Bolender	Undergraduate Student
Mr. D. J. Geist	Undergraduate Student
Mr. D. H. Kube	Undergraduate Student
Mr. G. E. Huling	Research Technician
Mrs. E. C. Oakley	Research Secretary

PUBLICATIONS AND CONFERENCE  
PRESENTATIONS

1. I. Kaufman and J. W. Foltz, "Self-Scanned Optical Sensor Using Elastic Surface Waves." Proc. IEEE, Vol. 57, Nov. 1969; 2081.
2. I. Kaufman, E. C. Crittenden, Jr., and H. G. Oltman, Jr., "Devices Combining Piezoelectricity and Photoconductivity," 1969 IEEE Ultrasonics Symposium, St. Louis, Mo., Sep. 1969.
3. V. O. Blackledge, I. Kaufman, K. A. Shaw and M. D. Sirkis, "Optical Sensor and Display Arrays Based on Element Scanning by Ultrasonic Surface Waves." International Symposium on Acoustic Surface Waves, IBM, Yorktown Heights, N.Y., March 1970.